

The galaxy ancestor problem

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Abstract

HST finds galaxies whose Tolman dimming should exceed 10 mag. Could evolution alone explain these as our ancestor galaxies? Or could they be representatives of quite a different dynasty whose descendents are no longer prominent today? We explore this latter hypothesis and argue that Surface Brightness Selection Effects naturally bring into focus quite different dynasties from different redshifts. Thus the HST $z = 7$ galaxies could be examples of galaxies whose descendents are both too small and too choked with dust to be recognisable in our neighbourhood easily today. Conversely the ancestors of the Milky Way and its obvious neighbours will have completely sunk below the sky at $z > 1.2$, although their diffused light could account for the missing Reionization flux. This Succeeding Prominent Dynasties Hypothesis (SPDH) fits the existing observations both naturally and well, including the bizarre distributions of galaxy surface brightness found in deep fields, the angular size $\sim (1+z)^{-1}$ law, 'downsizing' which turns out to be an 'illusion' in the sense that it does not imply evolution, 'Infant Mortality', i.e. the discrepancy between stars born and stars seen, and finally the recently discovered and unexpected excess of QSOAL DLAs at high redshift. If the SPDH is true then a large proportion of galaxies remain sunk from sight, probably at all redshifts. We show that fishing them out of the sky by their optical emissions alone will be practically impossible, even when they are nearby. More ingenious methods will be needed to detect them. It follows that disentangling galaxy evolution through studying ever higher redshift galaxies may be a forlorn hope because one will be comparing young oranges with old apples, not ancestors with their true descendants.

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I. INTRODUCTION

Attempts to decipher the evolution of the cosmos through studying high-redshift galaxies rely on the implicit assumption that those galaxies are, in some sense, the ancestors of the galaxies around us today. But what if they are not? We would not be comparing like with like and so be completely misled.

Tolman (1930) long ago argued that the surface brightnesses of galaxies would dim with redshift z as $(1+z)^{-4}$, indeed proposed it as a test for expansion. Now that the new wide-field camera WFC-3 on Hubble (Mackenty et al 2010) can routinely find galaxies at redshifts of 7 or more this raises serious questions as to their nature. Their Surface Brightnesses (SBs) as measured in our frame are to those of galaxies nearby, such as the Milky Way. Thus to be the ancestors of the local population they must have undergone enormous evolution (dimming by ~ 9 magnitudes) in lockstep with redshift. This might seem a fortuitous coincidence, particularly when the star formation histories of local galaxies show few signs of such dramatic evolution, testifying more to fairly constant rates of star formation throughout cosmic time, e.g. Tosi (2008).

Here we explore an alternative hypothesis: that the populations of galaxies which will show up at different redshifts are different from one another. They are not ancestors and descendants, but members of quite distinct families. For instance galaxies prominent at high redshift may be a physically compact, very high SB family which can take a lot of Tolman dimming, (≥ 10 magnitudes,) without disappearing from our sight at redshift 7 or more. The problem then becomes explaining where their descendants are today. The HST observations show that they are very small (sub kpc), dense, rather rare in co-moving density terms, and have no dust absorption. Taking into account their small sizes, and self-absorption by dust, which would naturally be high in such systems today, their contemporary descendants might be inconspicuous amongst the population of currently prominent galaxies.

Conversely, as we shall show, lacking dramatic evolution, more than half the light from a Milky Way will appear to have sunk beneath the sky at redshift 0.5, and every last photon by redshift 1.2. Our predecessor galaxies might therefore be totally invisible as individuals at higher redshifts, although their integrated light could very well swamp the output of those few compact high- z galaxies we can still detect out there. It hardly needs to be said that such a population of Sunken Galaxies could dramatically impact our ideas of cosmic

evolution. For instance they could supply the presently missing ultraviolet photons needed to re-ionise the Universe. They could also explain the excess of QSOALs, while Lilly-Madau plots showing the combined star-formation rates in the cosmos as a function of redshift would have to be seriously modified.

This hypothesis of Succeeding Prominent Dynasties (SPDH), as opposed to the current notion of an Evolving Single Dynasty Hypothesis (ESDH) has its roots in a number of older ideas. It is forgotten today, but before the Hubble was launched it was anticipated that Tolman dimming would rob the sky of almost all high- z galaxies, and it should have come as more of a surprise to find that this was not the case. Local galaxies tend to have a rather tight distribution of Surface Brightness, the explanation for which is still controversial (e.g. Davies, Impey & Phillipps 1999). But if it is a selection-effect the families of the wrong SB at any redshift will appear inconspicuous by comparison with other families of the right SB. An observer looking back through redshift space would thus expect to see, thanks to Tolman, different prominent families at different epochs. In particular he or she would expect to see the more compact objects at higher redshifts, and would find angular diameters $\propto (1+z)^{-1}$, which is exactly observed to be the case (Sect VI).

Some of these ideas were explored in 'The Visibility of High Redshift Galaxies' (Phillipps, Davies & Disney 1990) which built on earlier papers in 1983 (Disney & Phillipps) and 1976 (Disney). However the highest redshift being considered there and then was 0.3! The situation has certainly moved on in a number of respects; the observations of course, the supercession of photography by linear electronic detectors which makes the analysis markedly simpler, and the most fashionable cosmological model in which to set the calculations. Most importantly though, those earlier papers were missing a vital argument about the way to normalise Visibility, an argument that is here supplied in Sect 4, and which makes a significant difference to the main inferences.

The purpose of this paper is to push the Succeeding Prominent Dynasties hypothesis (SPDH) to the highest redshifts currently accessible to observation (~ 10). If it can be tested to destruction so much the better because, if it is true, then deciphering galaxy evolution will be very much harder, and perhaps impossible for generations to come.

The rest of the paper is arranged by section as follows:

(II) "The Narrow Window" gives a schematic outline of how the hypothesis works, and some of the conclusions it leads to.

(III) "Galaxy Visibility Theory" demonstrates by calculation the non-intuitive but dramatic nature of surface brightness selection effects, i.e. how two plunging curves mean that only galaxies huddled perilously close to the sky will be seen to any great distance.

(IV)"Imprisoned by Light" introduces a vital new argument to normalise Galaxy Visibility. It leads to the daunting conclusion that Low surface brightness galaxies too dim to turn up in the Schmidt photographic surveys will never be detectable in the optical, at least not for generations to come. Thus whole dynasties of sunken galaxies could exist, lurking just beneath the sky.

(V) "How galaxies sink from sight" incorporates Tolman dimming and cosmology into Visibility Theory to show how quickly redshift can drag galaxies below the sky. Thus Milky Ways would appear half sunk by redshift 0.5 and wholly sunk by $z=1.2$

(VI)"Why high redshift galaxies look small" argues that a combination of high intrinsic SB and Aberration will, at high z , bring to the surface an extremely compact dynasty of galaxies that are relatively inconspicuous nearby. Their apparent angular sizes will obey the angular diameter $\sim (1+z)^{-1}$ law as observed.

(VII) "The Descendants Problem" explains why the aforementioned $z \sim 7$ galaxies can leave descendants in our neighbourhood which we wouldnt find without a dedicated search partly because they will have choked on their own dust.

(VIII)"How Ellipticals sink". repeats the Visibility Theory of Section III but for giant Ellipticals which have a different light distribution. They should sink more slowly with redshift, leading to the illusion that they formed earlier than spirals. Fig 9 demonstrates how perilously close all visibly prominent galaxies must huddle to the sky.

(IX)"Downsizing, a different explanation." argues that because low SB galaxies sink at lower redshifts, there will be a downsizing illusion which has nothing to do with evolution but reflects a correlation between intrinsic SB and luminosity in the sense that intrinsically less luminous galaxies generally have dimmer intrinsic surface brightnesses. We briefly speculate about the so called Missing Dwarfs predicted by CDM.

(X) The "Discussion" covers several phenomena predicted by the SPDH including : (a) "Infant Mortality" the mismatch between the number of galaxies seen forming and the number later on seen. This is rather direct evidence that most high redshift galaxies have indeed sunk. (b) "Unexpected QSOALs" the surprising number of DLAs recently found at high redshift ; more evidence of a sunken population, and (c) "Reionization" which can be

explained by the diffused light of all the sunken dynasties . We conclude that the SPDH fits the high redshift galaxy observations in a natural and parsimonious way. It remains to be tested by looking for the Sunken and Choked Galaxies predicted to lie in large numbers, both near and far.

II. THE NARROW WINDOW

As anyone who has looked for M31 can testify, the problem of detecting galaxies in the optical is not so much lack of light as lack of contrast against the foreground sky[M31 has a V mag of 3.4 which spread over its size of roughly 3 by 1 degrees amounts to a SB = 21.2 V mag per sq arc sec , where the sky is about 21.5 at a fair site] This can be quantified by calculating the Visibility V of a galaxy as a function of both its Luminosity L and its Surface-Brightness-Contrast with the sky (in magnitudes per square arc second or μ), where the Visibility V is the relative volume in which it could be detected. The result is shown schematically in Fig 1. Irrespective of Luminosity there is a very narrow window in SB contrast in which it is easy to see galaxies. Calculations show that the FWHM for the Visibility of Spirals and other exponential galaxies is less than 3 magnitudes. And as is well known (Disney and Phillipps 1983, Davies et al. 1994) catalogues of galaxies appear to conform rather well to this theoretically predicted selection effect, though how many hidden galaxies lie undetected outside this narrow Visibility window is still a large and open question (Impey and Bothun 1997, Davies, Impey and Phillipps 1999) Some certainly exist: on the low SB side lie Local Group galaxies discovered as a result of enhanced star-counts, objects like Segue 1 with SBs ~ 6 mag dimmer than the peak in Fig 1 (Belokorov et al 2007); and on the high SB side Ultra-Compact Dwarfs distinguished from stars by their spectroscopic signatures with SBs ~ 7 mag higher (Phillipps et al 1998). Astronomers are surprised to find how narrow the SB window is. In Section III we justify it by calculation. Here we attempt a schematic explanation.

To get into a given galaxy catalogue an object must obey two independent criteria. It must be bright enough to be detected i.e. exceed some limiting catalogue apparent magnitude m_c , yet large enough in angular size to be detected as an extended object. That is to say its apparent angular diameter θ , measured at some specified isophote μ_c , must exceed the minimum catalogue limit θ_c .

If each galaxy is characterised by two parameters, absolute luminosity L , and intrinsic surface brightness (say central surface brightness μ_0 in mag arc sec^{-2} , or effective SB at half light $\mu_{1/2}$) then one can calculate the maximum distance d^m at which it can lie and still obey the magnitude criterion, and d^θ , the maximum distance at which it can lie and yet obey the angular criterion. Both distances scale as $L^{1/2}$ so we can set aside Luminosity as a simple scaling parameter and investigate the more interesting dependencies of d^m and d^θ on the surface brightness contrast $\Delta\mu = \mu_c - \mu_0$ between galaxy and sky.

Fig 1 illustrates what happens for objects with an exponentially declining light distribution (virtually all galaxies bar Giant Ellipticals; see later). The dashed (green) line shows d^m cubed (Volume not distance is the important measure), the smooth (red) line d^θ cubed, both as a function of $\Delta\mu$, the SB contrast. High SB galaxies with large $\Delta\mu$ s lie to the left, low SB ones with a small $\Delta\mu$ s to the right.

What is going on? Consider the dashed(green) line. At high enough SB virtually all of a galaxy's light will lie above μ_c , and $V^m \equiv (d^m)^3$ will not vary with the contrast, so the line is flat. But as the galaxy's SB is lowered (i.e. moves right) so the contrast $\Delta\mu = \mu_c - \mu_0$ drops, and more and more of its light falls below the limiting isophote μ_c , until, when $\mu_0 = \mu_c$ (ie $\Delta\mu = 0$) it vanishes altogether (i.e. d^m and hence $V^m \rightarrow 0$)

The red (smooth) line corresponding to $V^\theta \equiv (d^\theta)^3$ is more interesting. It has a fairly narrow peak because at high SB (to the left) the galaxy must be physically small, while to the right most of its light is dimmed below the limiting isophote μ_c , and what is left to measure above has a smaller and smaller apparent angular size until it vanishes altogether when $\mu_0 \rightarrow \mu_c$ and $\Delta\mu \rightarrow 0$.

Every galaxy in the catalogue must obey both criteria. Thus it must lie in the hatched, Wigwam-shaped area A beneath both the smooth (red) line and the dashed(green) line. Both lines plunge steeply, resulting in a narrow FWHM with a peak at P corresponding to an optimum contrast $\Delta\mu(P)$. Higher SB galaxies in region B lie above the smooth (red) line, and will be too small in diameter to be seen as galaxies at any significant distance, while lower SB galaxies to the right in region C lie above the dashed (green) line and will be too faint to see above the sky at any greater distance. Galaxies in D are completely submerged below the sky, even their cores being dimmer than the limiting isophote μ_c .

Fig.1, the Visibility or Wigwam Diagram, is central to our hypothesis, and fundamental to galaxy research, and as such deserves careful study. Note first

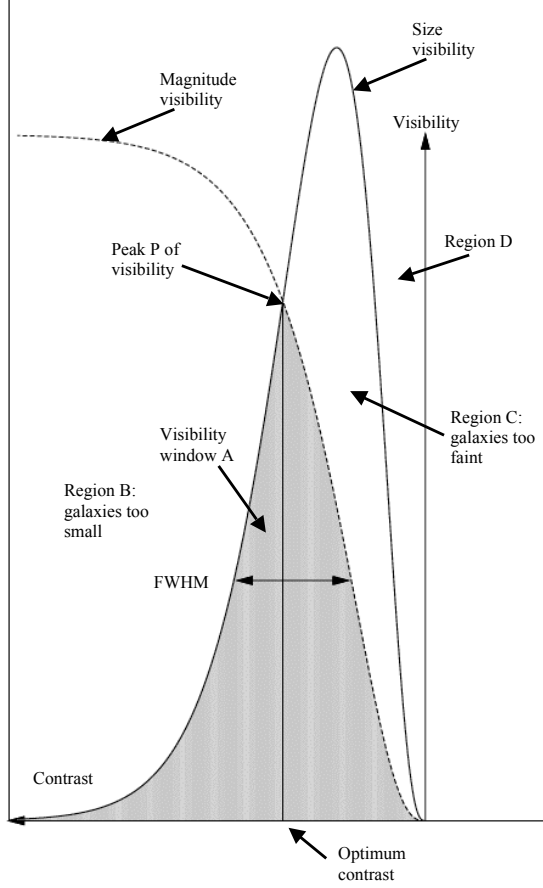


FIG. 1: Schematic Wigwam diagram of the Visibility (i.e. relative volume in which it can be detected) of an Exponential galaxy as a function of its surface-brightness contrast $\Delta\mu(\text{mag arcsec}^{-2})$ to μ_c the lowest surface brightness isophote that can be detected in the particular survey. In the usual convention lower SBs are to the right, while the contrasts $\Delta\mu$ increase to the left. The diagram is the same for all Luminosities which only effect the vertical scale. The green (dashed) line is the upper limit to the Visibility set by the apparent magnitude limit m_c of the survey, and so is called V^m in the text. The red (smooth) line is the upper limit to the Visibility set by θ_c , the angular-size limit of the survey defined at μ_c , and so is called V^θ in the text and labelled so in Fig 3. To be visible any galaxy must lie beneath both lines, and so must lie in the shaded region A. Those at the left in region B will be high SB objects that appear too small. Those in C will be low SB objects that appear too faint. Those in region D will have no part of their images showing above the sky; they are entirely sunk beneath it. In practice the FWHM of the Visible Window A is only 2.5 magnitudes. This should be compared with Tolman dimming of 3 mag at a redshift of 1, and 9 mag at a redshift of 7. As one looks to higher redshifts so Tolman dimming will cause galaxies to march from left to right across the diagram, passing through the Visibility Window A, the Wigwam, which is anchored in local coordinates by the brightness of the local sky (to which u_c is related). In this rendering the maximum heights of the two curves dashed, and smooth, have

that *is fixed in the observers coordinate system* and is independent of redshift. Any galaxy that is redshifted, and consequently dimmed by Tolman effects, will be moved rightward to lower SB. A prominent or high Visibility galaxy near the peak at P will slide rapidly down the dashed line to the right of A until it is only visible nearby(Actually it will slide much faster because its apparent luminosity, which normalizes the height of the curves, is also falling at the same time due to Tolman). Note second that the diagram applies to all (Exponential) galaxies, irrespective of Luminosity, which only changes the vertical scale. Note third that μ_c , the outer isophotal level, will be related to the sky-brightness (at the appropriate wavelength) but will generally be deeper thanks to the accumulation of photons per detector-pixel (See Sect. IV). Fourth the HWHM of the Visibility Window A is generally less than 2 mags. But redshift dimming by $(1+z)^{-4}$ corresponds in magnitudes to $+10 \log(1+z)$ thus 2 mags. corresponds to a redshift of less than 0.6. This implies that even at redshifts of a half, ancestor galaxies will be severely dimmed, and in many cases will be sunk out of sight entirely. So even at moderate redshifts ($0.5 \leq z \leq 1$) the argument has to be made that the galaxies we do detect out there really are the ancestors of the Milky Way and its catalogued neighbours.

If they are not our ancestors, then what else could they be? To answer that it is necessary to discuss Tolman dimming. One factor of $(1+z)$ arises from relative time-dilatation in the source, one from photon-weakening, i.e. photons shifting to lower energy along their line of flight. The other two arise from simple aberration, that is to say that the source was closer to the observer and therefore looked bigger by a factor $(1+z)$ in each dimension than it would do today.(i.e. the convergence angle of its light was set at emission not detection.)

Returning to Fig 1 aberration means that a source that is in region B, and is therefore too compact to have much Visibility nearby, can be apparently expanded by aberration and so appear relatively prominent at higher redshifts. To understand this, note that Fig1 has no vertical scale marked in; it shows the *relative* Visibilities of galaxies with different SB contrasts. Remove the high Visibility galaxies (e.g. Milky Ways) by redshift-dimming then other, intrinsically higher SB objects, will fill the peak of the Visibility Window instead. It is always the galaxies whose apparent SBs match at the peak (approximately at $\Delta\mu= 3$ to 4 mags) which at any redshift will appear most prominent, i.e. those for which

$$\Delta\mu' \equiv \Delta\mu(\text{intrinsic}) - 10\log(1+z) = \Delta\mu(P) = 3.5 \quad (1)$$

The narrowness of the Visibility Window (FWHM ~ 2.5 mag, as we shall prove in Sect III), by comparison with Tolman dimming, can lead to some very surprising phenomena and illusions. For instance:

(a) The apparent distribution of SBs among galaxies cannot change with redshift, for it is a consequence of the local window. This surprising prediction is observed(e.g. Jones and Disney 1997, see Fig 2). Tolman dimming is 3 mag by redshift 1 and 9 mag by redshift 7 , thus the observed constancy in Fig 2 is most unlikely to be a consequence of dramatic stellar evolution which is nowhere apparent in the archaeology of our own and neighbouring galaxies. (e.g. Tosi 2008, Tolstoy et al 2009)

(b) Galaxies at redshifts > 1 will sink below the sky, but their diffused radiation could still dominate the universe and lead to phenomena such as Reionisation.

(c) To be detected above our sky high- z galaxies must have very high intrinsic SBs , and thus be very small for their Luminosities. Unless galaxies are also undergoing dramatic size-evolution we must therefore be seeing out there a new and distinctly different dynasty.

(d) If less luminous galaxies also have dimmer intrinsic SBs, as evidence suggests, then that alone would lead to the illusion of downsizing i.e. dwarf galaxies will apparently only lift themselves above the sky at recent epochs (Sect IX).

(e) There will be another illusion which we dub Infant Mortality. Infant galaxies may briefly lift themselves above the sky while undergoing the vigorous star-formation associated with their birth then sink from sight leaving a shortage of older children.(Sect X)

(f) Those disappeared children should nevertheless turn up in absorption as an excess of QSOALs at high z (Sect X).

Once one knows what to look for, phenomena (a) to (f) are all plain to see in the observational literature.

Like Anthropologists galaxy astronomers certainly have an Ancestor problem . However its solution may be naturally found within the Succeeding Prominent Dynasties (SPDH) scenario .

III. AN OUTLINE OF VISIBILITY THEORY

The Visibility of galaxies is a subtle matter with a tangled history which, in the past, was complicated by the need to take account of photographic saturation, no longer generally

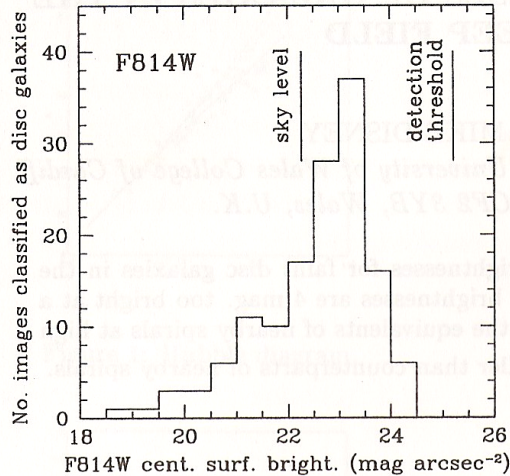


FIG. 2: The distribution of central Surface brightnesses of exponential galaxies in a typical Hubble Deep Field in this case the WFPC2 I-band. A connected pixel algorithm was used to identify images having ≥ 8 contiguous pixels (equivalent radius = 0.064 arc sec) above a detection threshold $\mu_L = 25.22$ (Vega System) in the F814 filter. Visual morphological classification was performed on all images brighter than $=28.0$. The galaxies classified as exponentials, based on the presence of discs and/or their light profiles on visual inspection, were fitted with exponential profiles and hence central surface brightnesses μ'_0 s. (Taken from Jones and Disney 1997). They are fairly sharply peaked at a surface brightness μ_0 1 to 1.5 mag dimmer than the sky, exactly as predicted by Visibility Theory (see Sect 6). Since such frames contain galaxies from a wide range of redshifts, and thus Tolman dimmings, it is very hard to understand such a sharp peak as anything but a profound selection effect operating in the observers frame of reference.

necessary. Some of the papers were incomplete (Disney 1976, Disney and Phillipps 1983, van der Kruit 1987) some were misleading (McGaugh 1996) and some were wrong (Allen and Shu 1979)

All we attempt to do in this section, and in the simplest possible way, is justify the narrowness of the Visibility Window A illustrated in Fig 1 because it is so crucial to the main argument and because it comes as such a surprise to most astronomers. To keep things simple we consider only exponential galaxies and ignore Tolman dimming and cosmology for now (see later). If we adopt de Vaucouleurs (1959) 2-parameter intensity $I(r)$ profiles for

galaxies, i.e.

$$\ln \frac{I(\theta)}{I(0)} = - \left(\frac{\theta}{\alpha} \right)^{\frac{1}{\beta}} \quad (2)$$

($\beta=1$ for pure Exponentials, $\beta=4$ for Giant Ellipticals, with hybrid galaxies in between) then we can reach the main results analytically. It is easily shown that the apparent luminosity, integrated over the image out to angle Θ is [$\beta=1$ henceforth until we reach Sect VIII.]

$$l(\Theta) = \int_0^\Theta 2\pi\theta I(\theta) \cdot d\theta = 2\pi I_0 \alpha^2 \left[1 - \left(1 + \frac{\Theta}{\alpha} \right) \cdot \exp\left(-\frac{\Theta}{\alpha}\right) \right] \quad (3)$$

so that as $\Theta \rightarrow \infty$ the total apparent luminosity

$$l_T = 2\pi I_0 \alpha^2 \quad (4)$$

where I_0 is the central SB and α the *angular* scale-length. Thus (4):

$$\alpha = \frac{1}{\sqrt{2\pi}} \times \sqrt{\frac{l_T}{I_0}} \quad (5)$$

If the angular radius out to the outermost detectable isophote I_c is $\Theta_{out} \equiv N \times \alpha$, which defines N , then the perceived angular diameter $\theta = 2\Theta_{out} = 2N\alpha$.

Thus

$$l(\Theta_{out}) = l_T \cdot [1 - (1 + N) \cdot \exp(-N)] \quad (6)$$

From (2)

$$\frac{\Theta_{out}}{\alpha} \equiv N = \ln\left(\frac{I_0}{I_c}\right) = (0.4 \ln 10) \times (\mu_c - \mu_0) \quad (7)$$

where μ_c and μ_0 are I_c and I_0 in magnitudes. So defining the *vital* SB contrast:

$$\Delta\mu \equiv (\mu_c - \mu_0) \quad (8)$$

$$N = (0.4 \ln 10) \Delta\mu = 0.92 \Delta\mu \quad (9)$$

Combining (4) (5) and (7) and recalling that $l = dex(-0.2m)$ and $I_0 = dex(-0.4\mu_0)$

$$\theta''(diam) = 2N \frac{1}{\sqrt{2\pi}} dex[-0.2(m - \mu_0)] \quad (10)$$

Or using $m - M = 5 \log d(pc) - 5$

$$\theta''(diam) = \frac{10}{d(pc)} \cdot \sqrt{\frac{2}{\pi}} \cdot N \cdot dex(0.2\mu_0) \cdot dex(0.2M) \quad (11)$$

And replacing μ_0 by $\Delta\mu$ using (8)

$$\theta''(diam) = \frac{10}{d(pc)} \cdot \sqrt{\frac{2}{\pi}} \cdot \{0.92\Delta\mu \cdot dex(-0.2\Delta\mu)\} \times dex(0.2\mu_c) \cdot dex(-0.2M) \quad (12)$$

It shows that angular size is a separable function of the absolute magnitude M and the SB contrast $\Delta\mu$, as one might have expected.

To get into a sample or catalogue with a minimum angular size θ_c a galaxy must then be at a distance d^θ (in pc) such that :

$$d^\theta \leq \frac{10}{\theta_c''} \cdot \sqrt{\frac{2}{\pi}} \times \{0.92\Delta\mu \cdot dex(-0.2\Delta\mu)\} \times dex(0.2\mu_c) \cdot dex(-0.2M) \quad (13)$$

which could also be written:

$$d^\theta \leq 10 \cdot \sqrt{\frac{2}{\pi}} \times \{0.92\Delta\mu \cdot dex(-0.2\Delta\mu)\} \times \left[\frac{1}{I_c \theta_c^2} \right]^{0.5} \times dex(-0.2M) \quad (14)$$

Which neatly separates the contrast, inside curly brackets, the catalogue, inside square brackets, and the Luminosity factors in the expression for $V^\theta \propto (d^\theta)^3$. Note that the contrast dependence inside the curly brackets clearly has a maximum, which explains the shape of the smooth (red) curve in Fig 1.

Likewise, to find d^m and V^m we can calculate the apparent magnitude of that fraction f of the galaxy-light lying inside the outermost detectable isophote. f is obtained simply by integrating Eqn (3) only to Θ_c , corresponding to I_c , in which case Eqn (6):

$$f(\Delta\mu) = 1 - e^{-N} \cdot (1 + N) \quad (15)$$

where $N = 0.92\Delta\mu$ as always. So

$$m = M + 5 \log d(pc) - 2.5 \log f(\Delta\mu) \quad (16)$$

And

$$d(pc) = 10 \sqrt{f(\Delta\mu)} \times dex[0.2(m - M)] \quad (17)$$

Thus the maximum distance d^m to which the galaxy can be detected, without exceeding the catalogue limit m_c is

$$d^m(pc) = 10 \cdot \sqrt{f(\Delta\mu)} \times \left[\frac{1}{l_c} \right]^{0.5} \times dex(0.2M) \quad (18)$$

where l_c is the apparent luminosity corresponding to m_c . In its cubed form (18) yields V^m the dashed (green) line in Figs 1 and 3 which reflects the monotonically falling nature of f [see (15)] as the contrast $\Delta\mu$, and hence $N = 0.92\Delta\mu$ vanish.

Having established the general shape of the red (smooth) and green (dashed) lines V^θ and V^m in Fig 1 (and 3) what about their intersection point P which will vary with their relative heights ? Dividing (14) by (18) :

$$\frac{d^\theta}{d^m} = \frac{N \exp(-0.5N)}{\sqrt{1 - (1 + N) \exp(-N)}} \times \sqrt{\frac{2}{\pi}} \cdot \sqrt{\frac{l_c}{I_c \theta_c^2}} \quad (19)$$

where recall that $N = 0.92\Delta\mu$. Fig 1 (and 3) is a plot (of $(d^\theta)^3$ and $(d^m)^3$ as a function of the SB contrast $\Delta\mu$ i.e. of N .

It is evident from the above equation that the relative heights of the two visibilities can only be adjusted through the pure number :

$$\Gamma_c \equiv \frac{l_c}{I_c \theta_c^2} = \frac{-0.4 dex(m_c - \mu_c)}{\theta_c^2} \quad (20)$$

determined by the catalogue parameters m_c , μ_c , and θ_c . Now it turns out (next section) that m_c and μ_c are closely linked to one another by photon statistics while θ_c is generally set by the telescope resolution. Thus in practice Γ_c has a narrow range. Hence the relative heights of our smooth (red) and dashed (green) lines, which define the Visibility Window, cannot sensibly vary by much, and in particular its narrow aperture in contrast ($< \pm 1.5$ magnitudes) and its Wigwam shape are more or less unavoidable as we shall see in the next section.

The net result of all the algebra is Fig 3 which looks very like the schematic Fig 1 but now is anchored in numbers, in particular the very narrow FWHM (2.5 mag), and the position of the Visibility peak P 3.5 mag above contrast zero. The actual curves and consequent Wigwam-shaped Visibility window were calculated from (14) and (18) assuming a value for Γ_c (eqn 20) of π typical of virtually all CCD surveys both in Space and from the ground (Fig 4, Sect 4). In looking at Fig 3 it is worth anticipating two points: (i) The contrast-zero point is locked to the absolute sky brightness being, for distant galaxies, about 5 mag

dimmer than the sky in Space, 6 mag dimmer than the (brighter) sky on the ground; (ii) The 3.5 mag contrast at the peak refers only to the central brightest point of an Exponential galaxy. Most of it huddles much closer to the sky (Fig 9). [A more detailed description of Visibility Theory can be found in Disney and Phillipps (1983), though it lacks the vital arguments of the next section; also see Ellis G.F.R et al. 1984)]

IV. IMPRISONED BY LIGHT

The precise shape and location of the Visibility Window for a given galaxy survey will depend on the relative heights of the red (smooth) and green (dashed) lines in Fig 3 which in turn depend on the number n_p of photons gathered by the detector per square arc sec. For instance if the smooth(red) line V^θ is lower than the green(dashed) V^m at all contrasts $\Delta\mu$, then it is only the smooth(red) V^θ , with its FWHM and peak, which define the Visibility Window which then might be quite different from the Wigwam calculated in Fig 3. It turned out that the relative heights were determined by the pure number Γ_c , but what determines Γ_c ? This is the important step in the argument missing from the 1983 paper.

Imagine a roughly circular source Θ arc sec in diameter where the detector has collected n_p /photons sq arc sec. The signal from the source

$$l = \frac{\bar{I}}{I_{sky}} \times \pi \left(\frac{\Theta}{2}\right)^2 \cdot n_p \quad (21)$$

where \bar{I} = a level of signal from the source in photons collected/ sq arc. sec. averaged over the whole source-area. I_{sky} is the foreground sky level and n_p is the total accumulated signal in photons/ sq arc sec. Then from (15)

$$\Gamma_c \equiv \frac{l_c}{I_c \theta_c^2} = \frac{\bar{I}(\pi/4) \cdot \Theta^2}{I_c \theta_c^2} \quad (22)$$

where I_c is the average level of signal within the outermost detectable contour in photons/ arc sec sq. Thus for the limiting case of the smallest sources detected in the catalogue $\Theta \rightarrow \theta_c$ And

$$\Gamma_c \rightarrow \frac{\pi}{4} \cdot \frac{\bar{I}}{I_c} \quad (23)$$

What are \bar{I} and I_c ? They will be set by signal-to-noise considerations. For the whole source the signal is given by (21) while photon-noise from the sky(assumed brighter than the source) is $\sqrt{\pi n_p (\Theta/2)^2}$

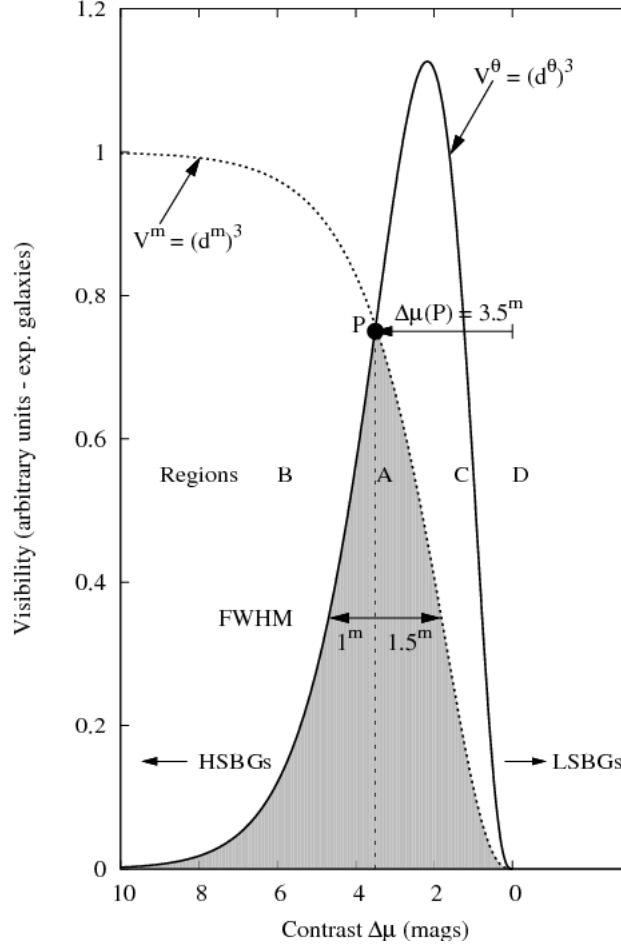


FIG. 3: The calculated Visibility Window for Exponential galaxies. The vertical scale shows the relative volumes within which galaxies with different surface-brightness-contrasts to the background (plotted horizontally) can be detected. Following the usual convention this contrast $\Delta\mu$, in mag, is plotted from right to left with high surface brightness, i.e. high contrast galaxies to the left, low surface brightness galaxies to the right. The maximum heights of the two curves V^m (dashed or green) and V^θ (smooth or red) assume a sample for which $\Gamma_c = \pi$, typical of all Exponential galaxies, save those hundreds of pixels across. This is a typical Wigwam Diagram for the Visibility of galaxies of all kinds (see later). Since the vertical scale is arbitrary the Wigwam Diagram is valid irrespective of Absolute Luminosity, just as it is valid irrespective of the absolute survey depth (deepest isophotal level μ_c) because the horizontal axis is given only in contrast $\Delta\mu \equiv (\mu_c - \mu_0)$ where the latter is the central SB, measured in magnitudes. To be detected galaxies must lie inside the Wigwam, the shaded area marked A, which we call The Visibility Window. Note how narrow it is, with a FWHM of 2.5 magnitudes with a peak P at a contrast of 3.5 magnitudes .Because the Window is so narrow, redshift dimming will quickly move galaxies rightward and out of sight into regions C and even D. For future reference¹⁵ note that even the V^θ (smooth or red) curve, by itself, has a FWHM of only 3 magnitudes.

TABLE I: Probabilities of a false positive (Single tail)

σ	1	2	3	4	5	6
Prob	0.16	.03	.0015	3×10^{-5}	3×10^{-7}	10^{-9}

so the S/N of the whole source $\equiv \sigma_m = (\bar{I}/I_{sky}) \cdot \sqrt{\pi n_p (\Theta/2)^2}$ or

$$\frac{\bar{I}}{I_{sky}} = \frac{\sigma_m}{\sqrt{n_p \pi (\Theta/2)^2}} \quad (24)$$

I_c will likewise be set by the S/N in the outermost isophote which we will assume is $q\Theta$ wide (defining q). The signal in that outer isophote $= I_c \cdot \pi \Theta \cdot q\Theta$

The noise in it $= \sqrt{\pi \Theta q \Theta n_p}$

And so $S/N \equiv \sigma_\theta = (I_c/I_{sky}) \cdot \sqrt{\pi \Theta q \Theta n_p}$

Thus

$$\frac{I_c}{I_{sky}} = \frac{\sigma_\theta}{\sqrt{\pi \Theta q \Theta n_p}} \quad (25)$$

We can thus insert (24) and (25) into (23):

$$\Gamma_c = \frac{\pi}{2} \cdot \sqrt{q} \cdot \frac{\sigma_m}{\sigma_\theta} \quad (26)$$

where q , defined to be the width of the outer isophote as a fraction of the diameter, depends only on the sizes of the sources at the limit of detection.

From (26) it becomes clear that estimating Γ_c , and hence the location of the Visibility Window, relies on picking appropriate values for the two limiting signal-to-noise ratios, σ_m referring to a whole image, and σ_θ to its outer isophote, which define the catalogue. If (but see later) the noise is dominated by photon-statistics, i.e. is binomial in nature, there is a rational way to select those ratios. They must be just high enough to avoid a significant number of false positives. As is well known in the Binomial situation the probability of a single false positive (i.e. single-tail) is given in Table 1.

Thus in a survey of a *single* CCD frame ($\sim 10^7$ pixels) a formal choice of a discriminating $\sigma_m = 5$ should eliminate all but a handful of false positives. For a survey consisting a fair number of CCD frames a S/N of 6 to 7 would be safer.

The case for σ_θ is different. The source has been selected; one needs only to be reasonably certain that the apparent outer isophote is real, i.e. that its probability as a false-positive is less than say 5 or 10 percent, in which case $\sigma_\theta \sim 1.5$ should suffice.

All that remains uncertain in (26) is q . Now for small extended sources containing only 10 to 20 optical pixels *altogether*, i.e. galaxies at the limit of detectability as such in Hubble Deep Fields, $q \leq 1/3$, i.e. the diameter must be ≥ 3 times the outermost isophote -width.

Thus for HDFs $\Gamma_c \approx \frac{\pi}{2} \cdot \sqrt{3^{-1}} \cdot \frac{7}{1.5} \approx 4.2$. However, if we had the luxury of a catalogue comprised of large galaxies > 100 pixels across $q \rightarrow 10^{-2}$ and hence $\Gamma_c \rightarrow 0.5$.

We can summarise the bounds on Γ_c as follows:

$$0.5 < \Gamma_c < 5 \quad (27)$$

where very large galaxies having hundreds of resolution elements per diameter are on the left, and extremely small galaxies having 3 to 5 are on the right.

Γ_c is so important because it determines the crossover point P , i.e. $\Delta\mu(P)$ and thus the nature of the Visibility Windows in diagrams such as Fig 1 and Fig 3. One can find $\Delta\mu(P)$ for a given Γ_c by equating V^θ to V^m and solving Eqn (19) for $\Delta\mu$. There are no solutions for $N < 2$ (i.e. $\Delta\mu < 2/0.92 = 2.2$) because then the dashed (green) line always passes above the smooth (red) line, and none for $N > 4$ ($\Delta\mu > 4.5$) because Γ_c must be < 5 [see Eqn. (27)]. In between there is a rather smooth, almost linear transition which passes through the $(\Gamma_c, \Delta\mu(P))$ points (2.5, 3.0), (3.2, 3.5) and (4.9, 4.4). See Fig 4. Thus Fig 3 (π , 3.5) is completely typical of all but the largest galaxies with hundreds of detector pixels per diameter.

We can summarize a situation, which is very much simpler than it might have been, as follows. A search for Exponential galaxies with a CCD detector will have a Visibility diagram much like Fig 3, i.e. a Wigwam Diagram. Such galaxies will only be found in a narrow Visibility Window centred at a contrast of between 3 and 4.5 magnitudes, and the FWHM of that window will be 1 mag to the high SB side, 1.5 mag to the low SB side, making a total FWHM of only 2.5 magnitudes in all. For very large (> 100 detector pixels in diameter) galaxies the situation is qualitatively different. Only the (smooth, red) curve in Fig 3 then matters, in which case the Visibility Window will be centred at a contrast of 2.2 magnitudes with a FWHM of 3 mags, 2 on the high SB side, 1 on the low (as assumed by Disney 1976, and reviewed by Impey and Bothun 1997).

To emphasise how implacably we are imprisoned in our local cell of light let us try to calculate a way out of it.

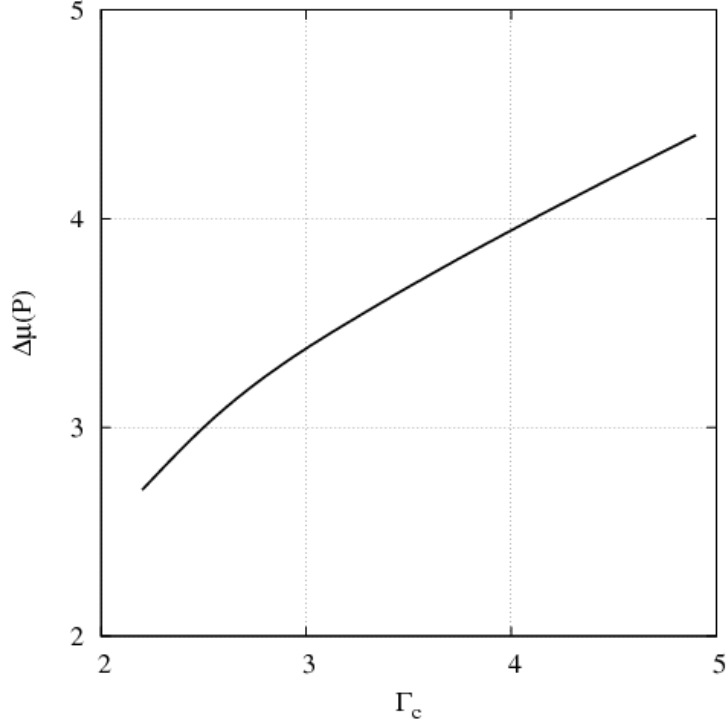


FIG. 4: The surface brightness contrast $\Delta\mu(P)$, in mag, at the peak of the Visibility Wigwam (see figs 1 and 3) for Exponential galaxies in surveys with different values of the pure number $\Gamma_c \equiv l_c/I_c\theta_c^2$ (see Eqn 20). Values calculated numerically using the procedure discussed below Eqn. 27. For the smooth (red) and dashed (green) curves to cross $\Delta\mu(P)$ must be > 2.2 (see Eqn. 27) and Γ_c must be < 5 for the smallest galaxies. Thus the practical range in $\Delta\mu(P)$ for nearly all surveys is narrow (3 to 4 mag) . Thus the Visibility curve shown in Fig.3 with $\Gamma_c = \pi$ and $\Delta\mu(P) = 3.5$ is very typical for Exponentials. Only very large galaxies with hundreds of pixels/diameter have Γ_c s less than 2.2. For them the smooth (red) V^θ Visibility curve is all that applies. [NB The algebra for Ellipticals is slightly different but otherwise an identical procedure leads to a crossover at $\Delta\mu(P) = 10.4$ mags for a Γ_c of 5 (See Figs 7 & 9)]

The number of galaxies \hat{N} of co-moving density ϕ we will detect in a survey covering solid angle Ω will be

$$\hat{N} \propto \phi \frac{\Omega}{3} \cdot d_{max}^3 \quad (28)$$

To move rightwards in Fig 3, i.e. to lower SB, it is the green (Dashed) line V^m which

matters, i.e. the galaxy's apparent magnitude must exceed the level of sky-noise by some discriminating S/N factor σ :

For a circular source of diameter Θ arc sec in an observation containing n_P photons per arc sec⁻² (24):

$$S/N \equiv \sigma = [\bar{I}/I_s] \cdot \sqrt{\pi/4 \cdot \Theta^2 n_P}$$

Now $\Theta \propto R/d$ (R = radius, d = distance) Thus

$$\Theta \propto \frac{\sqrt{L/\bar{I}}}{d} \quad (29)$$

or

$$d_{max} = \frac{1}{\sigma} \cdot \frac{1}{I_s} \cdot \sqrt{L\bar{I}} \cdot \sqrt{n_P} \quad (30)$$

Now

$$\Omega = \frac{TW}{t} \quad (31)$$

where T is the total survey time, t the dwell time per frame, and W the solid-angular area of the field of view of a single frame. This last equation is obvious but crucial because it argues that increasing dwell-time t in order to search for lower SB galaxies will not be so productive because it will, at the same time, reduce Ω and hence the Volume that can be explored.

Thus

$$\hat{N} = \frac{1}{3} \left(\frac{TW}{t} \right) \cdot \frac{1}{\sigma^3 I_s^3} \cdot (L\bar{I})^{3/2} \cdot n_P^{3/2} \quad (32)$$

But

$$n_P = I_s [D^2 t Q \Delta \lambda] \quad (33)$$

where D = telescope diameter, t = dwell time, Q is quantum efficiency of the system and $\Delta \lambda$ is the bandwidth of the detector in Angstroms say, and we have assumed, for low SB galaxies, that most of the collected photons come from the sky.

And so putting all together:

$$\hat{N} \propto \phi \cdot T \cdot \left(L \frac{\bar{I}}{I_s} \right)^{3/2} \times [D^3 t^{0.5}] \cdot \{W Q^{3/2}\} \quad (34)$$

a very important relation which neatly separates the galaxy properties(), the survey properties[] and the detector power { }.

From (34) we infer:

(a) To acquire a certain number galaxies of SB \bar{I} :

$$t \propto \left(\frac{I_s}{\bar{I}} \right)^3 \quad (35)$$

i.e. for a drop in SB of 1 mag the dwell time must be increased by 3 mags, or a factor of 16. Thus to escape entirely out of our Visibility Window (FWHM 2.5 mags) on the low SB side, we would need to increase dwell times by 2.5×3 mag or a factor of a thousand! *We truly are imprisoned in our lighted cell.* [Indeed the situation may be even worse than we have supposed. Thus far we have assumed that the two galaxy parameters L and \bar{I} are independent which may not be true. In so far as we can disentangle the two which requires a sample selected by non-optical (e.g. 21-cm.) means, the suggestion is that $\bar{I} \propto (L)^{1/3}$ (Garcia-Appadoo et al 2009, Chang et al 2011). If that is true then to see dim objects the dwell time t must increase not as $(\bar{I}/I_s)^3$ but as $(\bar{I}/I_s)^6$! See also Sect IX.]

(b) The detector figure-of-merit $\{ \}$ is higher for CCDs than for Schmidt photographic plates $\{36sq.deg, Q \sim 0.01\}$ provided the CCD ($Q \sim 0.5$) has > 2000 pixels a side. The grasp of any survey, by (34):

$$\propto T \times (D^3 \cdot t^{0.5}) \times W Q^{3/2} \quad (36)$$

which means that 1-month-long CCD surveys with 4-metre class telescopes will be an order of magnitude less effective for finding LSBGs than the combined Schmidt surveys covering the whole sky. But if photon-counting were the whole story then the Sloan DSS ought to beat the Schmidts by a factor of between 5 and 10, despite its very short dwell time ~ 100 secs. Unfortunately very low SB galaxies can only be detected if they look apparently large [Eqn. 24] when the unevenness of the sky-background, not its photon-statistics, becomes the predominant source of noise (Sabatini et al. (2003).

(c) The one ray of hope is the D^3 in Eqn. (36). Alas large telescopes produce larger images which over-fill the CCD-detector pixels for diameters > 2 to 3 metres on the ground because optics cannot be made arbitrarily fast. In that case $W \sim D^{-2}$ requiring $D \sim \bar{I}^{-3/2}$ for a given \hat{N} . Telescope diameters of 100 meters would be needed (see sect 6) to move one window-width dimmer than we can see now. Only low-noise, high-quantum-efficiency detectors of far larger physical size than CCDs offer any prospect of escape.

(d) Thus far we have estimated everything in terms of $\Delta\mu \equiv \mu_c - \mu_0$ where μ_c is a so far numerically unspecified SB, presumably connected to the sky-brightness μ_{sky} by signal-

to-noise considerations. Recall that it is the SB of the outermost detectable contour in a galaxy where that contour width is, by definition, a fraction q of the galaxy's total angular diameter Θ . We found ((25)) that

$$\frac{I_c}{I_{sky}} = \frac{\sigma_\theta}{\sqrt{\pi q} \cdot \sqrt{\Theta^2 n_P}} \quad (37)$$

For the smallest galaxies detectable in a survey $\pi q \sim 1$ so:

$$\frac{I_c}{I_{sky}} \sim \frac{\sigma_\theta}{\sqrt{N'}} \sim \frac{1.5}{\sqrt{N'}} \quad (38)$$

where $N' \approx \Theta^2 n_P$ is the total number of photons collected, largely from the sky, from *an area equivalent to the area of the whole source*.

So far as Space is concerned the high resolution of HST means that Θ is very small for faint galaxies ($\leq 10^{-1} \text{arcsec}$) so that extremely long integrations (tens of orbits) are needed to achieve N' s as high as 10^4 photons. It follows from (38) that

$$\mu_c \approx \mu_{sky} + (4.75 \text{ mag}) \quad (39)$$

Thus in Space μ_c is locked to the sky brightness. The position of the Visibility Window up there is not merely defined in terms of contrast but is in practice locked in *absolute* surface-brightness terms too.

The same is true on the ground though the argument is slightly more subtle. According to (34), for a given \hat{N} :

$$\frac{\bar{I}}{I_{sky}} \propto \frac{1}{L} \cdot \frac{1}{t^{1/3}} \cdot \frac{1}{D^2} \cdot \frac{1}{T^{2/3}} \cdot \frac{1}{W^{2/3}} \cdot \frac{1}{\phi^{2/3}} \quad (40)$$

from which it might seem that a sufficiently long dwell-time t might lead to the detection of arbitrarily dim galaxies. Not so because (40) ignores Tolman dimming. It is easy to show that such dimming modifies (40) to

$$\frac{\bar{I}}{I_{sky}} \propto (1+z)^2 \times \frac{1}{L} \cdot \frac{1}{t^{1/3}} \cdot \frac{1}{D^2} \cdot \frac{1}{T^{2/3}} \cdot \frac{1}{W^{2/3}} \cdot \frac{1}{\phi^{2/3}}$$

If, because of the $(1+z)^2$ term, you cannot afford z to rise above 0.2 say then to find sufficient (\hat{N}) galaxies you must increase the area coverage Ω in (28) by taking a number of

frames $\Omega/W = T/t$. Putting in reasonable values for W (one CCD) and ϕ it then transpires that to find a handfull of low SB L_* galaxies within $z \approx 0.2$ would require:

$$\frac{t}{T} \leq 10^{-4} \quad (41)$$

Now a pixel-matching (i.e. 2 to 3 M) telescope collects $n_P \sim 10$ sky-photons sec^{-1} arc sec^{-2} , so in an area of a 3 by 3 arc sec galaxy $n_P \sim 10^2$ sky photons/sec so that in a long campaign lasting $T = 10^7$ sec (i.e $t \approx 10^3 \text{sec}$) $N' = 10^5$ photons/galaxy-area. So from (38)

$$\mu_c \approx \mu_{sky} + 5.8 \text{ mag} \quad (42)$$

which again is locked in absolute terms to the SB of the terrestrial sky (which at most wavelengths is *at least* one mag brighter than it is at HST).

The fundamental point is that the Visibility Wigwam diagrams are fixed not only in contrast terms but *in absolute surface-brightness terms as well*.

An alternative way to look at the matter is to investigate how the dimmest galaxy (SB $\sim I_{min}$) one can detect improves with telescope diameter D. On the ground, because of the pixel-matching problem, $I_{min} \propto (DA)^{-2/3}$ where A is the physical area of the detector. In Space pixel-matching isn't an issue because the diffraction-limited angular resolution $\delta\theta \propto D^{-1}$. But then, for a fixed number P of pixels, the survey area $\Omega \propto P(\delta\theta)^2 \propto PD^{-2}$ and so again $I_{min} \propto D^{-2/3}P^{-1}$. In other words the telescope costs of escaping from the Visibility Window, be it in Space or on the ground, become exorbitant. A factor 10 improvement in I_{min} would imply an increase in telescope diameter of $10^{3/2}$ and hence in costs C of $10^{3\gamma/2}$ if $C \propto D^\gamma$. Since γ is usually reckoned to lie between 2.5 and 3, and certainly above 2, vast sums would be needed.

For all practical purposes then we *are* implacably imprisoned in our cell of light. Classes of low SB galaxies unresolved into stars, which cannot already be seen in Schmidt surveys, are beyond hope of discovery by optical means alone. It follows that large hidden populations of low surface brightness galaxies, both near and far, cannot be ruled out by optical observations alone. This is a much stronger statement than could have been made before and it relies on the arguments which led to eqn.(26)

V. HOW GALAXIES SINK FROM SIGHT

The Visibility Window depicted in fig 3 is immutable, mathematical and pinned in local coordinates because it shows the contrast to ones local sky, be it on the ground or in space. What we need to calculate next are the properties, in particular the sizes and intrinsic SBs ,of the kinds of galaxies, seen at different redshifts, which will make it through that narrow window, particularly near its peak, taking into account the Tolman effects described above, which both dim a galaxy and increase its apparent size.

The $(1+z)^{-4}$ factor rapidly becomes very significant by comparison with the narrow FWHM (2.5 mag) of the Visibility Window. Even at $z = 0.5$ many of the most Visible galaxies that were in region A (Fig 1) at low redshift would be translated into region C and be far too dim to see. They have Sunk. Their SB contrast now becomes:

$$\Delta\mu' \equiv \mu_c - \mu'_0 = \mu_c - [\mu_0 + 10\log(1+z)] = \Delta\mu - 10\log(1+z) \quad (43)$$

which implies that even galaxies at the peak of the Visibility Window at low redshift [where $\Delta\mu \sim 3.5$] will have zero contrast $\Delta\mu'$ i.e. will cross the green (dashed) line [Fig 1] and vanish entirely by a redshift of 1.2 To delineate that green (dashed) line recall that the fraction of light detected above the outermost isophote μ_c is given by Eqn 15 .Figure 5 depicts $f(\Delta\mu)$. More than 50 per cent of the light from a galaxy that would be at the peak nearby, has already been lost at redshift 0.5, 82 per cent at redshift 1, and all by 1.2. These figures alone are enough to query the feasibility of trying to study galaxy evolution by using deep fields.

The galaxies that will appear instead at the peak of the Window will be, as always, those with an apparent contrast $\Delta\mu'$ of ~ 3.5 mag. In other words their intrinsic SBs will be given by [see (1)]

$$\mu_0 \approx \mu_c - 3.5 - 10\log(1+z) \quad (44)$$

or, at $z = 0.5$, 1.8 mag more brilliant than optimally Visible galaxies nearby to us today at low redshift ($\mu_0 \sim 21.5V\mu$) and 3.0 mag more brilliant at $z = 1$. Indeed if one examines the Visibility Window (Fig. 3) one sees, down at the FWHM, that the $z=1$ galaxies now in

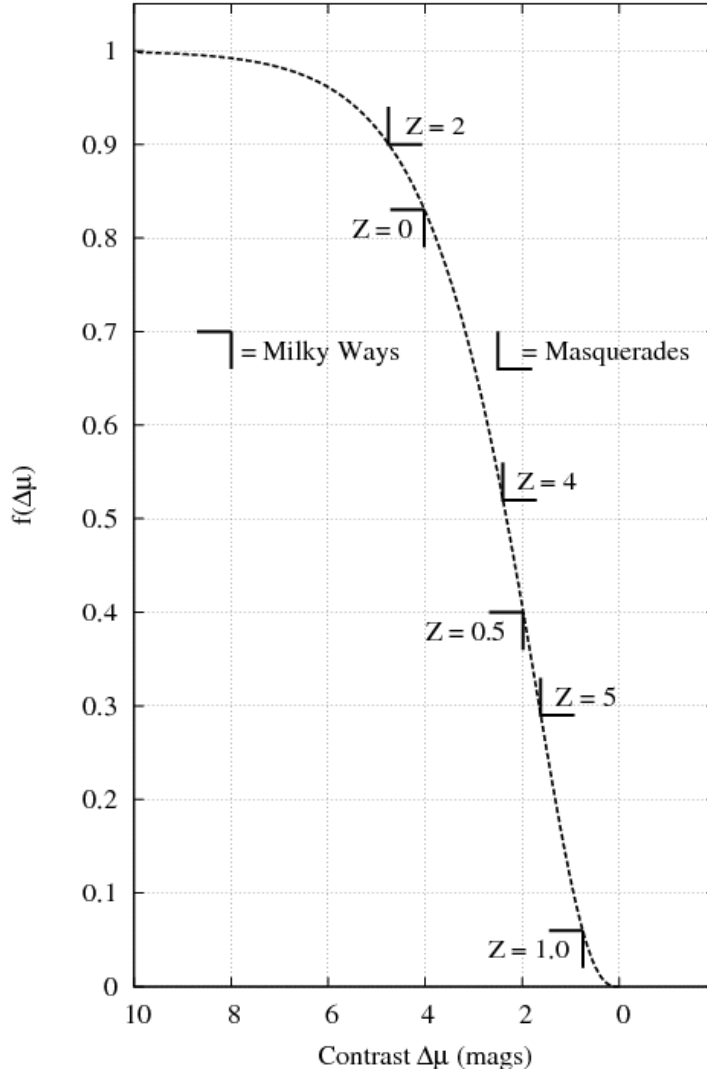


FIG. 5: The curve shows $f(\Delta\mu)$, the fraction of an Exponential galaxy's light seen above the outermost detectable isophote μ_c , plotted against the galaxy's contrast $\Delta\mu \equiv (\mu_c - \mu_0)$ in magnitudes. It is calculated from Eqn 15 with $\Delta\mu$ modified using Eqn (43). Thus a galaxy like the MW with an optimal contrast $\Delta\mu(P) \approx 3.5$ mag at $z=0$ has an $f(\Delta\mu) = 0.83$ there, as shown by the tick mark. By the time it is removed to $z=0.5$, $f(\Delta\mu)$ has dropped to 0.4, by $z=1.0$ to .06 and it disappears altogether at $z=1.2$ due to Tolman dimming. By contrast the tick marks to the RHS of the line show an L^* galaxy 9 mag higher in SB a so called 'Masquerade'. Even at $z=2$ ninety per cent of its light is still visible, and by $z=5$ nearly 30 per cent is still left. It only sinks completely at a redshift of 7.

the window must have emerged, or surfaced from Region B where they would be practically invisible at redshift zero.

How can redshifting, and hence dimming a galaxy render it more Visible? What the Visibility Window illustrates is the *relative* Visibilities of galaxies with different SBs. Rare but high-Visibility galaxies can be seen at great distances, common but low-Visibility galaxies may rarely turn up close enough to us to be noticeable in surveys. If now we remove the Local population to redshift 1, virtually all the previously prominent galaxies will sink below the sky thanks to Eqn. (43). Our high SB specimen therefore has much less competition, and is correspondingly more prominent. In addition it has gained through aberration. Whereas removing it to $z = 1$ would normally render it too small to seen as a galaxy (i.e. $\theta < \theta_c$) aberration may return it from the invisible region B into the visible window A.

In qualitative terms then, removing any population of galaxies to higher redshifts will drastically alter their relative Visibilities, so that the previously prominent specimens sink partially, or wholly, out of sight, to be replaced there at the peak of the window by intrinsically more brilliant galaxies that were relatively inconspicuous at low z because of their small apparent sizes. It is time to make things quantitative.

Begin by calculating the apparent magnitude $m(z)$ of galaxies that have peak Visibility (i.e. $\Delta\mu' \equiv \mu_c - \mu_0 \approx 3.5$ at redshift z taking into account both Tolman dimming, and Cosmology. Apparent luminosity:

$$l(z) = \frac{L}{4\pi d^2(z)} \cdot \frac{1}{(1+z)^2} \cdot f(\Delta\mu') \quad (45)$$

where f is the fraction of the light seen above the sky [Eqn.(15)] and $\Delta\mu'$ has been adjusted for redshift according to (43). Convert to magnitudes, with distances in Mpc. and

$$m(z) = 5[\log d(z)(Mpc) + 6] - 5 + 5\log(1+z) - 2.5\log f \quad (46)$$

$d(z)$ is the proper co-moving radial distance defined such that the co-moving volume element out at z is $\Delta\tau \equiv \frac{1}{3}d^2(z) \cdot \Delta\Omega \cdot \Delta d(z)$ corresponding to solid angle $\Delta\Omega$. [We dont need to employ the concepts of Luminosity distance or Angular-size distance because we incorporate the $(1+z)$ factors directly into equations such as (45) and (46).]

Cosmology now enters only through the functional dependence of the co-moving distance $d(z)$ on z . It can be a complicated function depending, as it may, on the various model-

parameters $\Omega_M, \Omega_\Lambda, \Omega_0, H_0$ and so on . Here we use the empty-universe approximation:

$$d(z) = \left(\frac{c}{H_0} \right) \ln(1+z) \quad (47)$$

because it is simple , and closely approximates the currently fashionable Λ CDM model. Between $0.1 < z < 10$ the discrepancy is a maximum of 12 per cent (at $z=1$) and for most of the range is much less [as can easily be checked using Ned Wrights very useful on-line Cosmology Calculator (Wright 2006)]. Given uncertainties as to which is the correct model, and K-corrections, dust and Evolution, this approximation is more than satisfactory.

Incorporating (47) into (46)

$$m(z) = M + 25 - 2.5 \log f(\Delta\mu') + 5 \log \left(\frac{c}{H_0} \right) + 5 \log[(1+z) \cdot \ln(1+z)] \quad (48)$$

Likewise to find $\theta''(z)$ use (47) for $d(\text{Mpc})$ and (12) becomes

$$\begin{aligned} \theta''(z) &= \sqrt{\frac{2}{\pi}} \cdot \{0.92 \Delta\mu' \exp(-0.2 \Delta\mu')\} \cdot (1+z) \\ &\times \frac{H_0/c}{\ln(1+z)} \cdot \text{dex}(-5) \cdot \text{dex}[0.2\mu_c] \cdot \text{dex}[-0.2M] \end{aligned} \quad (49)$$

where the $(1+z)$ term incorporates the aberration.

Fig 6 employs the last two equations to investigate the appearances of two galaxies at different redshifts. The first galaxy is a Milky Way, the second a hypothetical galaxy of the same intrinsic luminosity but with a SB no less than 9 magnitudes (4,000 times) higher. Notice first how quickly the MW sinks below the sky. By redshift half 56 per cent of its light has gone. By $z = 0.9$ the aberration cannot compensate for the sinking of its outer isophotes , and by $z=1.2$ it has sunk completely. One cannot expect to see healthy, i.e. more or less complete MWs much beyond a redshift of 0.5.

Now look at the hypothetical Masquerade which would be only 330 pc in diameter. Being $(4,000)^{-1/2}$ smaller than the MW its angular diameter at $z \sim 0.1$ would only be 0.2 arc sec. so unless it was close (< 50 Mpc.) it would, from the ground, masquerade as a star, hence its name. However by a redshift of 4 aberration is kicking in, while all the lower SB galaxies

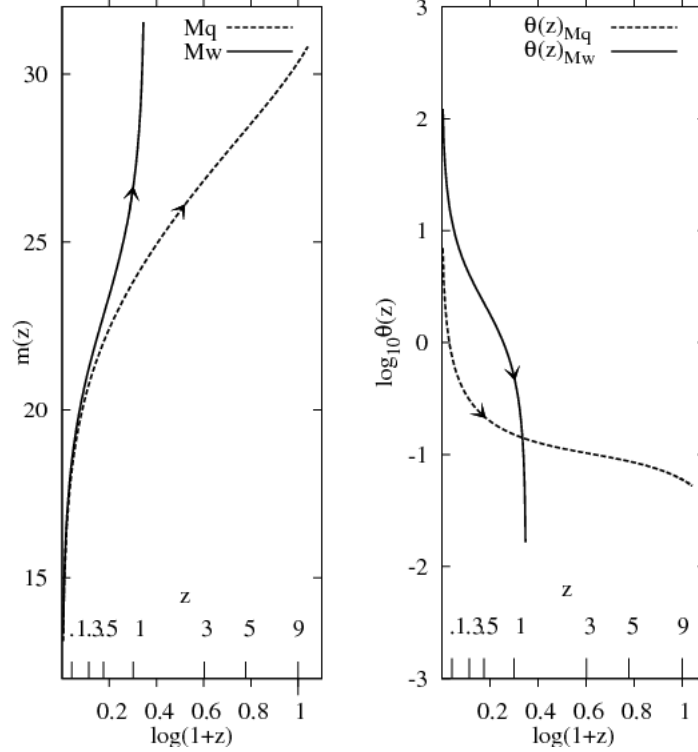


FIG. 6: The appearance of Exponential galaxies as a function of their redshift z . The apparent magnitudes $m(z)$ (left panel) and angular sizes $\theta(z)$ (diameter arc sec) (right panel) are shown for two objects of very different intrinsic surface brightness: a Milky-Way labelled Mw and a Masquerade labelled Mq which is a hypothetical galaxy of the same Luminosity but which is 9 mag (4,000 times) higher in SB, i.e. 9 mag more brilliant. The abscissa is redshift (plotted logarithmically, as are the other quantities). Follow first the magnitude $m(z)$ for the MW in the left panel. Because of redshift dimming, and shrinkage of its outer detectable isophotes against the sky, it rises more and more rapidly until, by $z = 1.2$ it will vanish even from the deepest Hubble Deep Fields [magnitude limits ≈ 30 depending on colour]. Follow second the angular size $\theta(z)$ (right panel) of the Milky Way. It falls rapidly at first then slows as a number of factors including Aberration kick in, then falls again catastrophically as $z \rightarrow 1$ when it loses contrast with the sky. It sinks completely out of sight when $z \rightarrow 1.2$ [See Eqn. (43)]. Now look at the Masquerade. Outer-isophote loss is negligible thus its $m(z)$ (left panel) increases more gradually with z so that its $m(z) \sim 29$ at a redshift ~ 7 . It is still visible to HST out there. Its angular size $\theta(z)$ (right panel) which is barely an arc sec at low z , hardly changes with redshift, due to the $(1+z)$ aberration term so it is distinguishable by HST as a galaxy even at $z \sim 7$.

would have sunk, or be sinking out of sight, so that by $z \sim 7$ it would be the most Visible L_* galaxy in sight because its apparent SB would be $\sim 21.5 \mu$, i.e. 3.5 mag brighter than the SB limit μ_c (See Sect VI). Its angular size would be ~ 0.6 arc sec making it distinguishable to the HST as non-stellar, while its magnitude would be ~ 29.5 (Vega). And if z increased above 7 so would its angular size, which would now be dominated by aberration. As we shall see later it looks very like the $z \sim 7$ galaxies being found with the WFC-3 camera on HST.

We can summarise this section as follows. The sheer size of Tolman dimming at the high redshifts accessible with HST makes it almost certain that the population of galaxies we see out there is very different from, and may not even be related to, our conspicuous neighbours today. The narrowness of the Visibility Window (Fig 3) compared to Tolman dimming is such that, without dramatic and fortuitous amounts of Evolution (up to and beyond 9 mag), our neighbours will fade dramatically beyond redshift 0.5 and sink altogether below our local sky at $z \sim 1.2$. Whatever the case nearby, the distant ($z > 1$) universe is almost certainly dominated by Sunken galaxies that are invisible to us, sunken galaxies that would surely alter our ideas on the star-formation history of the cosmos and its re-ionisation, could we but detect them. Those who aim to decode these matters by looking at the high redshift galaxies now visible with HST, even to decode galaxy evolution beyond redshift one-half, must first convince themselves that they are looking at our ancestors and not at a very different, higher SB population, the one that is most visible to us at that redshift, but which is inconspicuous nearby.

VI. WHY HIGH REDSHIFT GALAXIES LOOK SMALL

Technical developments, and in particular the fitting of the new WFC-3 camera to HST, make it almost trivial to find galaxies out to redshift 7, and perhaps higher. Its near IR sensitivity out to 1.7 microns, its resolution there (~ 0.1 arc sec.) and its field-of-view (4.8 sq arc mins) conspire to make it ~ 30 times faster for finding such objects than previous space cameras like NICMOS. Such galaxies are observed in their rest-frame UV (0.1 to 0.2 microns) where prominent breaks in their spectra at Ly- α and at the Lyman limit make for fairly unambiguous selection and photometric redshift measurements [e.g. Bouwens et al. (2010), Bunker et al (2010), McLure et al. (2010), Oesche et al (2010)]

If, as we are supposing, Surface Brightness selection through our narrow Visibility Window dominates the appearance of galaxies out there, one can make several strong predictions:

(a) All such high- z galaxies (indeed all Exponential galaxies in the deep frames) should have a narrow range of *apparent* surface brightness (~ 3 -4 mag).

(b) That range should be centred 3 to 4 magnitudes higher than the limiting isophotal value for the observational data in question.

(c) For the high- z galaxies Tolman dimming then implies that their intrinsic SBs must be very high, ~ 9 mags higher than prominent galaxies nearby. This in turn implies that they must be physically very small, otherwise they would be super-luminous.

(d) The apparent scale-length for such exponential galaxies should appear to decrease with redshift in a well determined way, i.e.:

$$\alpha \propto (1 + z)^{-1} \quad (50)$$

(e) Either such super-compact galaxies have detectable descendants nearby, or there must be some plausible mechanism for explaining their absence (next section).

Let us now compare these predictions with observations:

(a) The predicted constancy and scatter in SB is a direct consequence of the previous three sections and hardly needs further discussion.

(b) Where do we expect the central peak of the distribution of the SB's of galaxies in a Hubble Deep Field Window to lie? At peak we know (Sect 3): $\Delta\mu(P) = \mu_c - \mu_0 = 3.5$. For small galaxies in Hubble Deep Fields Eqn (39):

$$\mu(P) = \mu_c - 3.5 \approx (\mu_{sky} + 4.75) - 3.5 \approx \mu_{sky} + 1.25 \quad (51)$$

Fig 2 shows the distribution of SBs in one of the Hubble Deep Fields. As can be seen it fits the prediction of Visibility Theory very well because the sky brightness in the I band at Hubble is 22.5μ (Vega) .

Given Tolman dimming, evolution and dust absorption, all of which could be very large in these circumstances, especially in the rest-frame UV, it is very hard to understand Fig 2 as other than some kind of profound selection effect *operating in the observer's frame of reference*, as the SPDH suggests it is.

Oesch et al (2010) made a study of the structure of sixteen $z \sim 7$ galaxies in this sample and report "With an average intrinsic size 0.7 ± 0.3 kpc these galaxies are found to be extremely

compact, having an observed surface brightness $\mu_J \approx 26 \text{ mag arc sec}^{-2}$.” Their fig 2 shows the half-light radii tracking Absolute Magnitude so as to maintain that SB constancy. And in their fig 5 they extend the sample to objects in the range $z = 2$ to 8, finding that the measured (as opposed to corrected) UV SB which they interpret as a star-formation rate, remains relatively constant for the whole redshift range from $z \sim 7$ to $z \sim 4$. for galaxies with luminosities in the range $(0.3 \text{ to } 1)L_*$.

(c) Size evolution. For galaxies to be seen in the Visibility Window Eqn.(44) demands that their SB

$$\mu_0 \approx \mu_c - 3.5 - 10 \log(1 + z) \quad (52)$$

Now the physical scale-length $\alpha \propto \sqrt{L/I_0} \propto \sqrt{L/I_c} \cdot \sqrt{I_c/I_0}$ Thus for a given L and I_c

$$\alpha \propto \text{dex}[-0.2\Delta\mu] \propto [\text{dex}[-0.2(\mu_c - \mu_0)]] \quad (53)$$

therefore

$$\alpha \propto \text{dex}[-0.2\{3.5 + 10 \log(1 + z)\}] \quad (54)$$

therefore

$$\alpha \propto (1 + z)^{-2} \quad (55)$$

Thus the apparent scale-length will be, thanks to aberration, a factor $(1+z)$ larger, in which case we predict

$$r_{1/2} \propto (1 + z)^{-1} \quad (56)$$

Oesch et al (2010) compare their measured $r_{1/2}$ s with $(1 + z)^{-m}$ over the range $z = 2$ to 8 and report $m = 1.2 \pm 0.17$ for luminous $(0.3 \text{ to } 1) L_{*,z=3}$ and $m = 1.32 \pm 0.52$ for less luminous $(0.12 \text{ to } 0.3) L_{*,z=3}$ galaxies respectively. ”This is in agreement with previous estimates where the sizes were found to scale roughly according to $(1 + z)^{-1}$ ” (Bouwens et. al. 2004, 2006].

Earlier Buitrago et al , 2008) measured 80 giant galaxies ($M > 10^{11} M_{\text{solar}}$) in the range $1.7 < z < 3$ using NICMOS and split the sample into Discs and Spheroids. Discs are 2.6 ± 0.3 smaller than today, and Spheroids 4.3 ± 0.7 smaller. The implied stellar densities in the past at $\approx 2 \times 10^{10} M_{\text{solar}} \text{ kpc}^{-3}$ ”are very high and as high as Globular Clusters today.” The Disc measurements too are obviously consistent with $r_{1/2} \approx (1 + z)^{-1}$.

The same fall-off in physical size with redshift proceeds all the way from $z = 0$ to $z = 7$ with $R_{1/2} \approx (1 + z)^{-1}$. For instance Ryan et al (2011) have recently used WFC-3 in a 15-colour search to isolate a sample of early-type galaxies, this time in the interval $z=1.6\pm0.6$, and compared their sizes with a very large sample of equivalent SDSS galaxies at $z \sim 0.2$. Again they parameterise the size decline as $R_{eff} \propto (1 + z)^{-m}$

and find m is mass-dependent this time. And

$$m(M_{\star}) = -1.8 + \log \left(\frac{M_{\star}}{10^9 M_{sun}} \right) \quad (57)$$

yielding $m \sim 1$ for massive galaxies, and a statistical decline over all objects of a factor 4 between redshifts 0 and 1.6

The decline in galaxy-size with redshift is the most remarkable and consistent result in all the Hubble deep-field observations. It is predicted, indeed demanded by the SPD hypothesis in which Tolman dimming brings successively more compact galaxies to light at higher redshifts, while sinking entirely out of sight their less compact companions. [NB :As an aside, the confirmation of the prediction that angular size should $\propto (1 + z)^{-1}$ *might* be taken, a la Tolman, as rather direct evidence, so far lacking, that the Universe *is* expanding. It would rely on the assumption that intrinsic SB does not change much with redshift, as suggested by the archaeology of nearby galaxies.]

VII. WHERE HAVE THE DESCENDANTS GONE?

What happened to the spectacularly high SB galaxies we see back at redshift 7? Have they evolved away either by mergers or passive dimming, or are their descendants lurking around us today? We shall argue that their direct descendants could well be present in our neighbourhood but would have passed unnoticed because they would be extremely inconspicuous, and for three different reasons. First their compact physical sizes translate into angular sizes so small that their Angular-Size Visibility V^{θ} will be down on normal galaxies by a factor of 60 cubed. Secondly the dust-grains in such compact objects would be on average 60 times closer to neighbouring stars than they would be in a Milky Way galaxy today, and therefore be 3,600 times more effective as absorbers. Very little of their optical light would therefore escape making even the nearest of them exceedingly faint. And finally, in co-moving terms, they appear to be pretty rare which implies that the nearest of them

would be far enough away to make them, in terms of angular size, barely distinguishable from stars. Take these arguments one by one:

(a) Visibility:

For compact objects it is Angular-Size Visibility V^θ which counts. According to Eqn.(25) the most visible objects at redshift 7 must have a SB of $10 \log(1+7) = 9$ mag higher, and therefore a diameter 4.5 mag, or 60 times smaller than the galaxies in our vicinity. Thus for a given luminosity their angular sizes would be 60 times smaller, and their Visibilities $60^{-3} \sim 10^{-5}$ less. They will be extremely inconspicuous.

(b) Internal absorption. Large disc galaxies typically lose half their light to internal dust absorption (Disney, Davies and Phillipps 1989, Soifer Helou and Werner 2008), but compact galaxies ought to lose vastly more. One will see into a disc-galaxy \sim one mean-free-path λ where $\lambda = 1/n\sigma$ where n is the particle density, and σ the particle cross-section for absorption. Shrinking the disc radially by a factor 60 will increase n by $\sim 60^2$, so the physical depth from which one could detect light would, crudely speaking, decrease by the same factor, leading to a loss of apparent luminosity $\sim 60^2 \sim 9$ magnitudes. In other words once a disc becomes optically thick, compacting it further cannot increase the apparent SB, and its apparent optical luminosity will decrease with its area.

(c) Rarity and apparent angular size. Mclure et al (2010) fit a Schechter luminosity function to the faint end of the high z sample [where the statistics are "better"] and arrive at a co-moving density $\phi^* = 7 \times 10^{-4} \text{Mpc}^{-3} \text{mag}^{-1}$ which is more than an order of magnitude below the local value. Ignoring clustering the expected distance to the nearest one from us ought to be $\sim (3/4\pi\phi^*)^{1/3} \sim 7$ Mpc. [distance modulus ~ 29] and as the physical size ~ 20 kpc / 60 ~ 300 pc., the angular size of the nearest one would be ~ 10 arc sec, whilst most would look stellar. They would also be very faint, even the nearest $z \sim 7$ descendant to us would have a B magnitude of $[M_* + (m-M) + 9 \text{ mag (dust)}] \sim -20 + 29 + 9 \sim 18$ magnitude.

Attempts have been made to find ultra-compact galaxies by setting spectroscopic fibres on bright starlike objects superposed on clusters (Phillipps et al, 1998, Drinkwater and Gregg 1998). There was some limited success with the discovery of Ultra-Compact-Dwarf galaxies. However we would expect that most, and certainly most of the bolometrically luminous ones, will be choked in their own smoke(dust). They might however turn up in dedicated searches in the FIR.

The above discussion is highly simplistic, but the conclusions are so strong that one hardly needs to qualify them further. Even if they survive intact around us today the descendants of redshift 7 Exponential galaxies would pass unnoticed without a dedicated and extensive search in the FIR.

VIII. HOW ELLIPTICAL GALAXIES SINK

For simplicity we have so far concentrated exclusively on Exponentials. We now turn to giant Ellipticals which have the softer light distribution:

$$\ln \left(\frac{I(\theta)}{I_0} \right) = - \left(\frac{\theta}{\alpha} \right)^{1/4} \quad (58)$$

though that also implies a small amount of luminosity in a sharp pip in the core. At first sight it will look as if Ellipticals have very different Visibility functions from Exponentials, reaching their peak angular-size Visibility V^θ at a central SB no less than 7 mag brighter than Exponentials (Disney, 1976). However that turns out to be an artefact of the parametrization, and if a more physical SB measure $\mu_{1/2}$ (the SB at half light radius) is introduced then one finds [e.g.Davies 1990] that the Elliptical and Exponential Visibilities lie almost on top of one another, but with the FWHM of the Ellipticals being somewhat broader (4.2 mag as opposed to 2.5).

The algebra is much the same with the following modifications:

Eqn (3):

$$L(\infty) = 8!\pi I_0 \alpha^2 \quad (59)$$

In Eqn. (8): $\{\}$ $\rightarrow \{(0.92)^4 \exp(-0.92\Delta\mu/2)\}$

where the maximum of $\{\}$ occurs at $\Delta\mu = 4/0.46=8.7$ mag.

Also in (8):

$$\sqrt{\frac{2}{\pi}} \rightarrow \sqrt{\frac{2}{\pi 8!}} \quad (60)$$

d^n is identical but with $f(\Delta\mu)$ Eqn (15) replaced by $f_E(\Delta\mu)$ where

$$f_E(\Delta\mu) \equiv \frac{L(\Delta\mu)}{L(\infty)} = 1 - e^{-y} \left(1 + y + \frac{y^2}{2!} + \dots + \frac{y^7}{7!} \right) \quad (61)$$

with

$$y = (\theta/\alpha)^{1/4} = 0.92\Delta\mu \quad (62)$$

To plot the two Visibilities V^θ and V^m together we need first to adopt a value for Γ_c , and as we shall be most interested in apparently small distant galaxies we adopt a value at the upper limit of the Γ_c range of $\Gamma_c = 5$ (Eqn 21). That leads to a crossover point P at a contrast $\Delta\mu(P) = 10.4$ mag and thus to the Visibility diagram shown in Fig 7

Once again notice the two Visibilities intersect (at P) and the result can only be another discontinuous, sharply peaked Wigwam Visibility function limited on the right by V^m and on the left by V^θ . The FWHM of the combined Visibility curve enclosing the Visibility Window A is 4.2 mag, 1.7 mag on the Low SB side, and 2.5 mag on the High. The normalisation shown is such as to make $V^m \rightarrow 1$ as the Contrast $\Delta\mu \rightarrow \infty$. The Visibility shape, and some of the subsequent consequences, are different from Phillipps et al (1990) because there no cognisance was taken of Γ_c , and so there were was no unambiguous way to adjust the relative heights of V^θ and V^m .

Exactly as for Exponentials, Tolman dimming and Cosmology can be added to yield the apparent magnitude $m_E(z)$ and angular-size (diameter) $\theta_E''(z)$ as (see Eqn (44):

$$m_E(z) = M + 25 - 2.5\log f_E(\Delta\mu') + 5\log(c/H_0) \\ + 5\log[(1+z) \cdot \ln(1+z)] \quad (63)$$

where $\Delta\mu' = \Delta\mu - 10\log(1+z)$

while (47):

$$\theta_E'' = \frac{4}{\sqrt{4\pi \cdot 8!}} \cdot \{(0.92\Delta\mu')^4 \exp(-0.92\Delta\mu'/2)\} \\ \times (1+z) \cdot \frac{H_0/c}{\ln(1+z)} \cdot \text{dex}(-5) \cdot \text{dex}(0.2(\Delta\mu_c)) \cdot \text{dex}(-0.2M) \quad (64)$$

[The dex(-5) scale-factor accounts for the difference between the 10 pc in (m-M) and the Mpc used in H_0 .]

Fig 8 shows how the apparent magnitudes and sizes of giant Ellipticals fade with redshift. It is the analogue to fig 6 for Ellipticals, and like that diagram it too compares a galaxy of

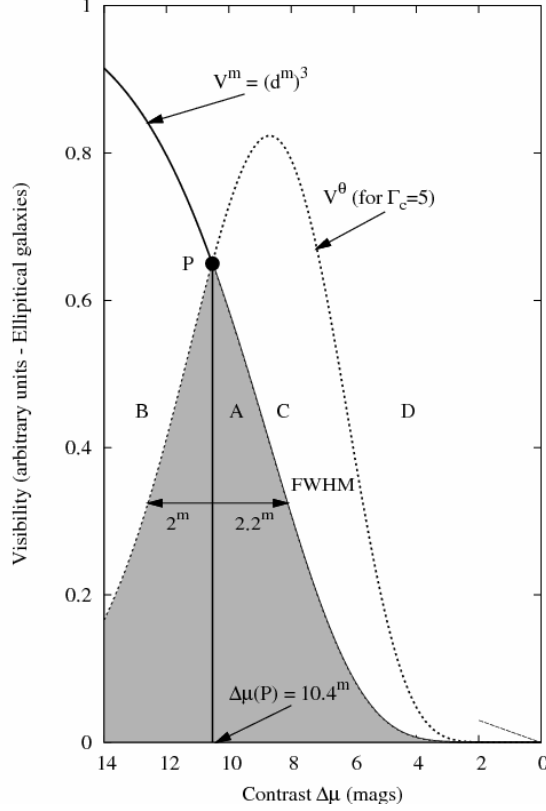


FIG. 7: Visibility as a function of surface-brightness-contrast $\Delta\mu \equiv (\mu_c - \mu_0)$ for Giant Elliptical Galaxies. The magnitude-limited Visibility V^m is normalised to 1 at high contrast i.e. high SB towards the left because all the galaxy's light will show above the sky then. The angular-size Visibility V^θ is the humped function. To the left its apparent size shrinks as, for a given luminosity, a galaxy must physically shrink as its SB increases. To the right it shrinks as more and more of its outer light is lost below the sky. The relative heights of V^m and V^θ are determined by the pure number $\Gamma_c = l_c/I_c\theta_c^2$ which must have a value close to 5 for all but very nearby galaxies hundreds of pixels in diameter (Sect IV). The actual Visibility is the lower envelope of both curves i.e. the shaded area marked A with a peak at P where the two Visibilities intersect to make a Wigwam. Only galaxies within A will be detected in a survey with limits (l_c, μ_c, θ_c) in the combination Γ_c as above. Galaxies in B will appear too small to be distinguishable as such, those in C too faint, those in D both too small and too faint. The FWHM of the Visibility window A is 4.2 mag, as opposed to 2.5 for Exponentials (see Fig 3). The location of the Elliptical peak P is at a contrast of $\Delta\mu(P) = 10.4$ mag, far higher than the Exponential peak at $\Delta\mu(P) = 3.5$ because, by comparison, Elliptical light distributions rise towards a sharper peak towards the core. However that peak contains very little light and so a fairer measure of the SB of a galaxy is the SB at half light $= \mu_{1/2}$, and a fairer comparison of the Visibilities of the different kinds of galaxies is made using their $\mu_{1/2}$ s to measure a contrast ' $\Delta\mu_{1/2} \equiv (\mu_c - \mu_{1/2})$ ', see Fig 9. [NB galaxies hundreds of pixels across have lower Γ_c s,

'normal, i.e. 'local' SB with a Masquerade, that is to say one which has a SB 9 mag more brilliant so as to give a maximum Visibility at a z of 7. It is interesting to compare Figs 8 and 6:

First notice the gentler slopes of $m(z)$ for the Es at high z . They do not fade away so quickly with z because they have a light distribution with a steep core, and this reflects in a difference between $f(\Delta\mu)$ (Eqn 15) and $f_E(\Delta\mu)$ (Eqn 61). So while a Milky Way dies completely, both in size and magnitude at $z=1.2$, $m(z)$ for a Giant gE doesn't reach the typical HST Deep Field limit of ~ 29 until $z \sim 2$. This extra Visibility range in V^m allows the Aberration to kick in more decisively ensuring the much more upturned $\theta_E(z)$ curves at high z . Thus the Normal gE would appear large enough to be seen as a galaxy with HST out to a redshift of 4-5 if, by $z = 2$, it hadn't already faded in magnitude below 29.

Comparing Fig(8b) with (8a), the Masquerade Elliptical (i.e. the one with a SB 9 mag more brilliant than a Normal gE) is too compact to lose much of its outer skirt of light below the sky so that it is only dimmed by distance, Cosmology, and the Tolman $(1+z)^{-2}$ effect. The magnitude-difference between Normal and Masquerade is entirely due to the aforesaid skirt-effect.

In summary, Normal Giant Ellipticals ought to be seen out to higher z s ($z \sim 2$ with HST) than discs of the same Luminosity ($z=1.2$). This is the opposite conclusion to that reached by Phillipps et al (1990) and is accounted for purely by Γ_c (Sect 4). This could give the misleading impression that gEs formed before other galaxies.

The one dramatic difference between gEs and Exponentials is the position of $\Delta\mu(P)$ at the point where the Visibility reaches a maximum, i.e. at the centre of the Visibility Window A; $\Delta\mu(P) = 10.4$ for Ellipticals there whereas for Exponentials it = 3.5 . But this is an artefact of the parameterisation. Ellipticals have a pip of light in their core which yields a correspondingly bright μ_0 which however is representative of very little luminosity in total. Better therefore to use $\Delta\mu_{1/2}$ where :

$$\Delta\mu_{1/2} \equiv \mu_c - \mu_{1/2} \quad (65)$$

and $\mu_{1/2}$ is the SB *at* the half-light radius.

It is trivial to show:

$$(\mu_{1/2} - \mu_0)_{Exp} = 1.8 \quad (66)$$

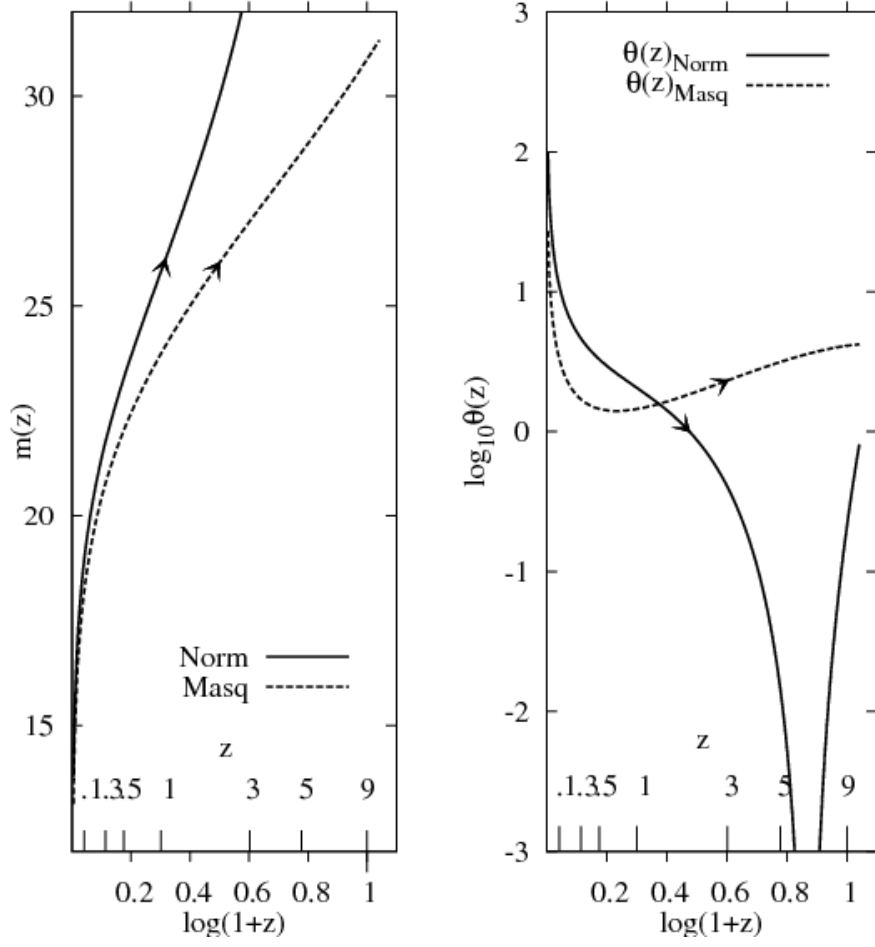


FIG. 8: The apparent magnitude $m(z)$ (left panel) and angular size (right) (diameter in arc sec) of an L^* Elliptical with normal SB [$\mu_0 \sim 15\mu, \mu_{1/2} \sim 23\mu$ in V band] and a Masquerade L^* Elliptical with a SB 9 mag more brilliant, as a function of redshift z . The normal gE crosses the Hubble Deep Field line (~ 30 mag) at $z \sim 2$ but the Masquerade reaches $z \sim 5 - 6$ before it is extinguished, because it loses very little outer light below the sky. For angular sizes, aberration kicks in so the Masquerade reaches a minimum angular size of ~ 2 arc sec at $z \sim 1$ and it apparently grows gradually thereafter. [The odd Aberration effect seen on $\theta(z)$ for the Normal gE is of no consequence, because by then its $m(z)$ has long since fallen below the sky.] Compare with Fig 6 for Exponentials (see text). For a given Luminosity Ellipticals can be seen significantly further away than Exponentials, which might give the false impression that they formed earlier.

Thus

$$\Delta\mu_{1/2}(P) = 3.5 - 1.81 = 1.7 \quad (67)$$

for Exponentials while for Ellipticals :

$$(\mu_{1/2} - \mu_0)_E = 8.4mag \quad (68)$$

Thus

$$\Delta\mu_{1/2}(P) = 10.4 - 8.4 \approx 2.0 \quad (69)$$

So in terms of a more representative measure of SB, the half-light SB $\mu_{1/2}$, the Visibilities of both breeds of galaxies lie almost exactly on top of one another, see Fig 9. It is a remarkable diagram that ought to give galaxy astronomers food for thought and we discuss it further in Sect IX. For now, at least, it argues that both extreme light distributions lie so close to one another, as far as Visibility is concerned, that so should all the intermediate types.

IX. DOWNSIZING; A DIFFERENT EXPLANATION

Another remarkable phenomenon among apparently faint galaxies is downsizing [Cowie et al (1996), Heavens et al, (2004), Thomas et al, (2005), Noeske et al (2007a, 2007b), Perez-Gonzalez et al (2008)]. In purely observational terms it is the appearance of lower luminosity and dwarf galaxies in apparent-magnitude selected samples only at lower redshifts ($z \leq 0.5$). And when they do appear they have comparatively blue colours and strong emission lines. If interpreted in terms of the ESD hypothesis it requires giant galaxies to form their stars first and dwarfs last, the very reverse of expectations based on Hierarchical Galaxy Formation, the fashionable cosmogonic hypothesis.

But downsizing, as we shall next argue, can also be an entirely natural outcome of the alternative SPD scenario, where it has no implications for the ordering of galaxy evolution. The only assumption required is that lower luminosity galaxies have, in a statistical sense, dimmer intrinsic surface brightness. Because of obvious selection effects such an assumption is not easy to demonstrate unequivocally, but most observations, as well as common sense, speak in its favour. For instance observations of HI- selected samples, which are unaffected

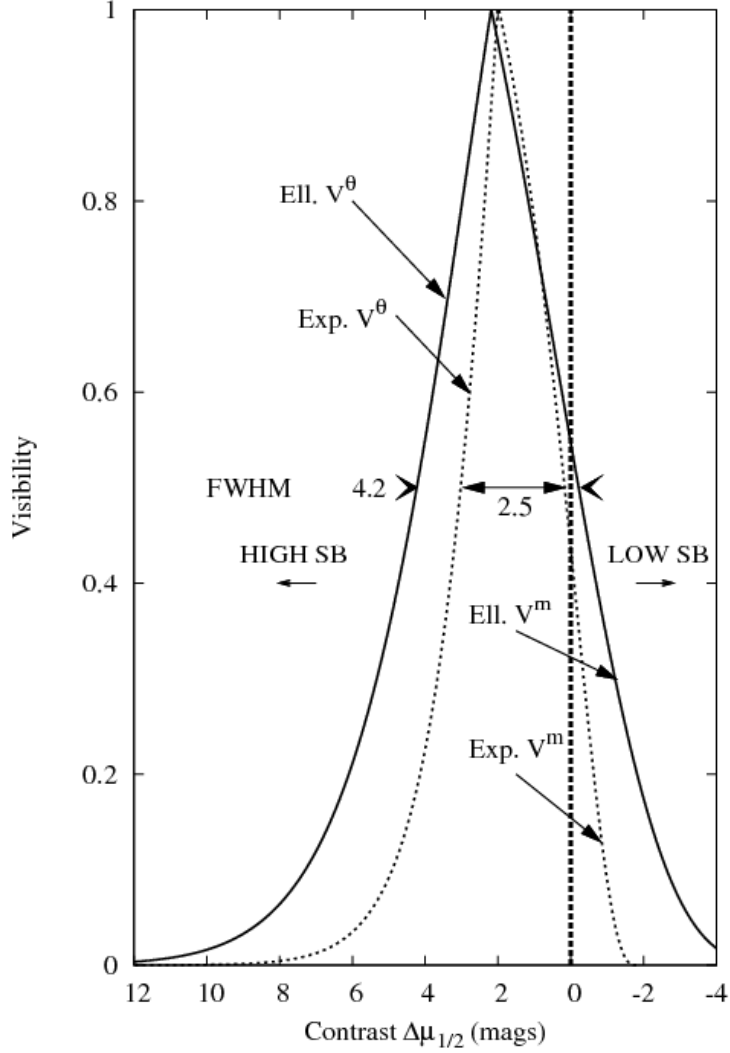


FIG. 9: The Visibilities of both extreme morphologies of galaxy as a function of their contrast $\Delta\mu$ with the sky, this time expressed in terms of their half-light surface brightnesses $\mu_{1/2}$ (Exponentials dotted, Ellipticals solid) . Now $\Delta\mu \rightarrow \Delta\mu_{1/2} \equiv (\mu_c - \mu_{1/2})$. In this more physically representative measure the two Visibility Wigwams fall almost on top of one another. They continue to the right of $\Delta\mu_{1/2} = 0$ simply because half of their light lies below their $\mu_{1/2}$. What is most remarkable is how perilously close both Wigwams huddle to the sky. Galaxies that are marginally dimmer, for instance Dwarfs, or higher z objects, will quickly disappear altogether. That suggests a natural explanation for downsizing as a selection effect which has nothing to do with evolution. [And what about the so called Missing Dwarfs in the CDM paradigm?]

by optical selection-effects, certainly show such a correlation [Garcia-Appadoo et al. 2009, Chang et al 2011] with

$$SB \propto L^{1/3} \quad (70)$$

implying global stellar-densities that are independent of Luminosity L . The $1/3$ then arises because the path length through a more luminous galaxy scales in that proportion.

The rationale for downsizing under the SPDH is immediately apparent in Fig 9. What we see there is that visible galaxies of all types ought to huddle perilously close to the limit set by the local sky. And observations going back to Holmberg (1965), Freeman (1970), Disney (1976) and Davies et al (1994) testify that that this is indeed the case observationally. If now dwarf galaxies carry the further handicap of a lower intrinsic surface brightness then they will naturally be the first to sink below the sky. A smaller amount of redshift-dimming should suffice to sink dwarfs entirely out of sight whereas giants will still be visible further out. And, observationally speaking, that is down-sizing.

To see how potent this kind of downsizing is we calculate how rapidly the Visibility of an Exponential galaxy (most dwarfs are Exponentials) will fall if we lower its SB according to (69) and then redshift it. If we start with an Exponential of optimum SB (i.e at the peak of the Visibility Window with $\Delta\mu = 3.5$ mag) lowering its SB will run it towards the right in Figs, 1, 3 and 9 i.e. towards the boundary determined by d^m and hence V^m . In those V^m expressions the intrinsic SB enters explicitly only through $f(\Delta\mu)$, or if redshift-dimming is allowed for in addition then through $f(\Delta\mu')$ where as usual $\Delta\mu' = \Delta\mu - 10\log(1+z)$. We can thus estimate what happens to the Visibility of a lower luminosity galaxy purely as a result of its extra SB dimming, by comparison with an L_* galaxy of normal, i.e. local SB. Both galaxies will of course fade with redshift but the dimmer dwarf will fade by more as it is quickly swallowed up by the sky. The situation is best summarised in the following Table 2 for 3 galaxies, an L_* , an $0.1L_*$ and an $0.01L_*$, all obeying (69) and with the L_* having optimum SB at the apex of the Visibility Window at $z=0$.

TABLE 2

Recall that f is the fraction of a galaxy's light still visible above sky, and that $f^{3/2}$ is proportional to the Visibility. The Giant doesn't sink completely until $z \approx 1.2$, the Low Luminosity galaxy has virtually gone by $z=0.7$ and the Dwarf by 0.4.

The other important aspect of downsizing as observed is that the low luminosity and

TABLE II: DIMMING AND DOWNSIZ-
ING

z	L/L_*	$\Delta\mu$	$\Delta\mu'$	$f^{3/2}$
0	1	3.5	3.5	0.76
0.1			3.1	0.69
0.3			2.4	0.52
0.4			2.0	0.41
0.5			1.7	0.31
0.6			1.5	0.25
0.7			1.2	0.17
0.8			1.0	0.11
1.0			0.5	0.02

z	L/L_*	$\Delta\mu$	$\Delta\mu'$	$f^{3/2}$
0	0.1	2.7	2.7	0.6
0.2			2.3	0.5
0.3			1.9	0.38
0.4			1.	0.17
0.5			0.9	0.09
0.6			0.7	0.05
0.7			0.4	0.01
0.8			0.2	0.002

z	L/L_*	$\Delta\mu$	$\Delta\mu'$	$f^{3/2}$
0.1	0.001	1.8	1.8	0.35
0.1			1.4	0.2
0.2			1.0	0.11
0.3			0.65	0.04
0.4			0.3	0.005

dwarf galaxies are bluer and have stronger emission lines at a given redshift. But that could be explained by a natural SB-selection-effect. Galaxies approaching total immersion would be far more prominent if they were undergoing temporary bursts of star-formation, with a consequent increase in SB. Take the dwarf in the table at $z=0.4$. If its SB were to increase by 0.35 mag we can see that its Visibility would increase by a factor $(0.04/0.005)$ or 8, and if by 0.7 mag then by over 20. (The 'Half-baked' appearances of many HDF galaxies could be due to the extra star-formation required to lift such galaxies above the sky.)

In summary then the SPD hypothesis has a natural explanation for the downsizing observations in terms of Visibility. It assumes only that intrinsic SBs generally fall with Luminosity, and implies nothing about Evolution.

[PS: One wonders if a similar effect could explain the so called MISSING DWARFS problem which afflicts CDM (e.g. Klypin et al 1999). If the correlation between SB and Luminosity in Eqn (69) holds all the way down to very faint objects then their SBs and Visibilities would render them exceedingly hard to find, even nearby. Eqn (69) implies that $\Delta\mu_{1/2} = -1/3 \cdot \Delta M$. Thus a .001 L^* Exponential Dwarf would have a $SB = -1/3 \times 7.5 = 2.5$ mag dimmer than a giant at the peak of the Window, and its Visibility would consequently be very small. And if the correlation were slightly steeper, e.g. $\Delta\mu_{1/2} = -1/2 \cdot \Delta M$, which is probably not ruled out by the observations, then the $\Delta\mu(P)$ would be 3.5-(7.5/2), i.e. would be negative and such a Peak dwarf would be totally and irretrievably sunk below the sky at *any* redshift.]

X. DISCUSSION

If the universe is expanding then the associated Tolman dimming should render conventional galaxies undetectable at high z . Most should be heavily affected by the sky at redshift 0.5, all totally submerged by redshift 2. The fact that we can easily see galaxies out to redshift 7 means either that conventional galaxies have undergone the most dramatic evolution (The Evolving Single Dynasty or ESD hypothesis), or that the galaxies out there belong to different populations, different dynasties, whose descendents haven't so far been identified nearby (The Succeeding Prominent Dynasty Hypothesis or SPDH).

If our neighbourhood galaxies are role models then high redshift galaxies are truly bizarre. They are one or two orders of magnitude smaller in physical size, while their intrinsic surface

brightness must be 9 mag or 4000 times higher. Moreover, and this is even more extraordinary, they must have systematically adjusted their sizes and their SBs over cosmic time so as to squeeze themselves through the narrow Visibility Window at all the various intermediate redshifts where they can be seen. Such dramatic evolution is hardly consistent with the archaeology of nearby galaxies whose star-formation-histories seem rather steady and quiescent over time. Furthermore the high redshift galaxies are, in co-moving terms, rather rare (e.g. McLure et al 2010), too few in number to provide the ultraviolet radiation needed to re-ionize the IGM at redshifts between 6 and 11. And this difficulty is compounded if downsizing is a physical, as opposed to an illusory phenomenon, for the lower luminosity galaxies form too late to contribute to the ultraviolet budget when it would be necessary.

The SPD hypothesis requires no such dramatic evolution, and explains both downsizing (Sect IX) and galaxy-expansion (Sect VI) as illusory phenomena, the side effects of Visibility Theory, i.e. SB-selection. It also leads, through its postulation of large numbers of sunken galaxies, particularly at high redshift, to a natural solution for the Re-ionization Problem. And it is interesting that there are two other strong hints in the recent literature at the presence of such a sunken high-redshift population: one due to what we call Infant Mortality, the other to an excess of high- z QSOALs. We discuss these next.

INFANT MORTALITY. In the ESD hypothesis the stellar mass density at any epoch ought to equal the accumulated rate of star formation over all preceding epochs:

$$\rho(t_0) = \int_0^{t_0} \dot{\rho}(t) \cdot dt = \int_{\infty}^{z_0} \dot{\rho}(z) \cdot \frac{dt}{dz} \cdot dz$$

In the SPD scenario this however will no longer apparently be the case because in moving from z to $z+dz$ some lower SB galaxies will appear to sink beneath the sky due to Tolman dimming (*i.e.* $-(\partial\rho/\partial z)_{sink} \cdot \Delta z$) while other higher-SB objects will apparently surface (thanks to aberration) to partially replace them. Thus the integral above should be replaced by

$$\rho(t_0) = \int_{\infty}^{z_0} \left[\dot{\rho}(z) \cdot \frac{dt}{dz} + \left\{ \left(\frac{\partial\rho}{\partial z} \right)_{Surf} - \left(\frac{\partial\rho}{\partial z} \right)_{Sink} \right\} \right] \cdot dz$$

where the net $\{\}$ could be either positive or negative, depending on the distribution of galaxy numbers as a function of intrinsic SB. All one can say for sure is that there is

no reason to expect a good match between observed stellar densities and accumulated past star-formation. And such a mismatch has been noted by many observers. For instance Perez-Gonzalez et al (2008), p 248, remark : "We find that the cosmic SFR densities estimated by differentiating the evolution of cosmic stellar mass density do not match the observations based on direct SFR tracers as also noted by Rudnick et al (2006), Hopkins and Beacom (2006) and Burch et al (2006). The mismatch up to $z \sim 2$ (a factor of 1.7) could be explained by changing the IMF And as z rises from 2 to 4.5 the discrepancy is larger (a factor 4 to 5 ..) " This highly significant mismatch is in the sense that less galaxies are observed in each redshift bin than the total of previous SF would lead one to expect. Under the SPD hypothesis this would be naturally explained if most high redshift galaxies sink below the sky once their most vigorous period of SF comes to an end. This is rather direct evidence of the SPDH, though perhaps not conclusive.

SUNKEN DLAs. Even where they cannot be seen in emission, sunken galaxies should still show up in absorption, in particular as QSOALs, probably of the Damped Lyman Alpha (DLA) i.e high-column-density variety. The number detected in the redshift range :

$$N(z).dz \propto \int_z^{z+\Delta z} \int_0^L \phi(z, L) \cdot A(z, L) \cdot g(z) \cdot dz \cdot dL$$

where $g(z).dz$ is the physical path-length derived from some cosmological model, $\phi(z, L)$ is the co-moving density of galaxies of luminosity L , and $A(z, L)$ is their effective cross-section per galaxy. As is well known (e.g. Wolfe et al 2005) if $\phi(z, L)$ corresponds to the local value for L^* galaxies, $A(L, z) \sim$ observed optical area of L^* s, and a reasonable extra boost (by a factor 2-15) is allowed for the dwarf contribution associated with the L^* s, then there is a fair correspondence with the observed $N(z)$ i.e. between 5 and 10 percent of high redshift QSOs ($z \leq 6$) have DLAs in their spectra. Unfortunately that sets no absolute limit on ϕ , and hence on a population of sunken galaxies, without some independent knowledge of the cross -section $A(L, z)$ which is not available. One can always increase ϕ by decreasing A . Nevertheless if the SPD hypothesis is true one might expect a mismatch between the z -dependence of $N(z)$ and the number density inferred from the rate of galaxy formation,

in the sense that that there will probably be more DLAs in the distance, corresponding to the extra galaxies out there which have sunk from sight. And in a qualitative sense at least that is what seems to be observed in the large SDSS sample of QSOs recently analysed by Prochaska and Wolfe (2008). Instead of a decline in cross section [our $N(z)$, their $l(z)$] and in co-moving HI density with rising redshift, caused by the decline in the number of already-formed disc galaxies with z , they find instead an increase by a factor of 2 between $z=2$ and $z=4.5$ (only 2 Gyr.) which they find "a profound and surprising result". There may be other explanations (which they mention) but it seems qualitatively consistent with the idea of a larger proportion of sunken galaxy absorbers at higher redshifts.

So there is significant indirect evidence in favour of the SPD hypothesis and its implication that the universe is stuffed with Hidden Galaxies. Moreover the SPDH is an almost inevitable consequence of Visibility Theory, which is hardly radical, but usually neglected. If Hidden galaxies are not ubiquitous it will take a great number of fortuitous coincidences to explain why all the detected galaxies in the universe have arranged themselves, at all redshifts, so as to squeeze through our narrow, parochial, Visibility Window (e.g. Fig 2).

Indirect evidence is all very well but direct evidence of Hidden Galaxies, particularly of such a rich population as the SPD hypothesis requires, would be far more persuasive. If Hidden galaxies are so common why haven't they turned up in dedicated searches with large telescopes, and why haven't far more of them appeared in the blind HI surveys (that are of course free of SB selection) that we and others have recently been carrying out?

With the benefit of hindsight we can answer both questions. The argument at the end of Section IV is new. We and others understandably supposed that a large enough optical telescope, fitted with CCDs and dedicated to the search, would turn up Low SB galaxies, if they exist. But alas that is simply not true, and Eqn (34) reveals why. When it comes to searching for LSBGs Tolman dimming together with the small sizes of CCDs more than cancel out their high quantum efficiencies and infinite dynamic ranges. The Schmidt photographic surveys, completed in the 1980s, represent the best that can be done. That is a depressing admission, but there seems to be no practical way around Eqn.'s (34) and (41) in Sect IV.

The blind 21 cm surveys which we and others have carried out such as HIPASS, (Meyer et al 2004), HIJASS(Lang et al 2003), AGES(Cortese et al 2010) and ALFALFA (Giovanelli et al. 2005) have turned up only one truly invisible giant galaxy, Virgo HI21 (Davies et

al. 2004, Minchin et al, 2005, 2007), and there is even some dispute about that (Haynes et al 2007). In fact HIPASS 's failure to turn up a single invisible galaxy among its 4000 detections in the Southern hemisphere, has been used to claim (Doyle M.T. et al 2005, Wong et al 2006, Wong et al 2009) that Hidden galaxies do not exist, or are very rare (and we were party to that claim). Our re-analysis (Disney 2008, Disney and Lang 2011) shows however that the claim was based on a grossly optimistic estimate for the reliability of the optical identifications involved. When clustering is allowed for there could well be 100 dark galaxies in the sample i.e. HI sources that have been misidentified with optically bright objects that are fortuitously close by in both angular and redshift space. And blind surveys with a larger dish won't improve the situation, because their extra resolution is exactly counterbalanced by the extra distance at which the typical sources will be found (Disney 2008). Anyway when objects such as Malin 1 certainly exist, a giant LSBG 200 kpc across, containing $> 10^{11}$ solar masses of HI, (Bothun and Impey 1989) one has to be cautious about blind-scanning techniques in general. Such objects nearby will be much larger than the scanning radio beams, and so tend to be lost in the process of noise subtraction. None of the existing blind HI surveys, in our opinion, sets strong constraints on the presence of HI-rich Hidden Galaxies nearby. In such surveys absence of evidence is not strong evidence of absence.

Nevertheless it remains vital to pin some of the hypothetical Hidden Galaxies down. At low redshifts in the HI suspicious optical identifications should be vigorously pursued with interferometers. And the compact descendants of the $z=7$ galaxies, now small, faint and choked in dust (Sect VII) might still be locatable in the FIR relatively nearby. At high redshift sunken Milky Ways beyond a z of 1.2 may have regions, if seen in emission lines, that will still rise above the sky in objective prism surveys. Moreover they, and their Elliptical counterparts ($z > 2$) should still give rise to faint supernovae which may turn up in what otherwise appears to be intergalactic space, and a start has been made in such surveys (Hayward et al 2005).

In one sense one must hope that the SPD hypothesis is wrong, for if it is right then extra-galactic research is going to be so much harder. The obvious program of decoding galaxy-formation and evolution simply by building larger instruments such as JWST or ELT to look at fainter, more distant objects wont work because a given dynasty of galaxies will remain visible through our Visibility Window for a only a limited range of redshifts,

i.e. for only a restricted portion of its life. We might see the infants of one dynasty, the children of another, the adults of a third, and the grizzled elders of a fourth only among our neighbours.

On the other hand the SPD hypothesis has strong epistemic advocates. It is extremely parsimonious (Gauch 2005) relying as it does only on Tolman dimming and Visibility Theory, the last of which we have been at some pains to explain and defend. Neither is it the least radical in the sense that it employs assumptions outside very ordinary physics. And it is vulnerable in that it predicts the existence of whole dynasties of galaxies which are presently undetected, but whose existence it may eventually be possible to affirm or deny.

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